THE UNIVERSITY OF ALBERTA

CULTIVATOR CHASSIS MECHANICS

by

(C) SHANKAR TIWARY

A THESIS

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies for acceptance, a thesis entitled "Cultivator Chassis Mechanics" submitted by Shankar Tiwary in partial fulfilment of the requirements for the degree of Master of Science.

ABSTRACT

The cultivator, being one of the most common cultivating implements in Canada, was selected for field testing to obtain information on (a) the application of forces on the cultivator chassis and (b) the analysis of forces.

The project was divided into two parts. The first part included (a) the decision about the number of forces acting on the chassis (static and dynamic conditions), (b) design and calibration of transducers to sense the forces, and (c) instrumentation. The second part consisted of (a) testing of transducers in the field, (b) collection of data, and (c) analysis of the forces.

Field tests were conducted at the Ellerslie Research Farm of the Department of Agricultural Engineering, University of Alberta. The variables studied in the project were depth, speed, cutting unit, bulk density, and daily moisture content variation in the field. These variables were used in testing the hypothesis that the forces acting on the chassis were in equilibrium. Reasonably good agreement in force balance was obtained. A moment balance of the forces could not be obtained in most of the cases and required more accurate values of all the forces.

In describing the forces and their behavior, two variables (depth and speed) were studied and the following conclusions were drawn:

1. An increase in depth or speed increased the horizontal component of soil force. However, an increase in depth had far greater effect than an increase in speed.
2. The vertical component of the resultant soil force varied directly with depth. The direction also changed (downward to upward) at shallow depths (less than 4 in.). The relation between speed and vertical force was significant only at 6 in. depth.
3. Correlation between the ratio of vertical to horizontal components of resultant soil force and depth was highly significant and a second degree polynomial was used to represent the relationship.
4. A small increase in the total draft generally resulted in a decrease in wheel reaction and an increase in vertical force on the hitch. However, a much larger increase in the draft had just the opposite effect on the wheel reaction and vertical force on the hitch. Increased wheel slip and wheel sinkage altered the tractor-cultivator geometry resulting in a decrease in the vertical force on the hitch. Momentary maximum values of three times the average values were obtained.

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ABBREVIATIONS AND SYMBOLS

cm	Centimeter
C_α	Soil metal friction
C	Centigrade
DEF	Lines of deflection
c	Depth of operation
d_1	Distance between the line of action of horizontal force on shanks and ground surface
d_2	Distance between horizontal force on shanks and tip of the cutting tool
F_0	Area of inclined tool
F	Vertical force on wheel reaction transducer
gm	Gram
h	Drawbar height
in.	Inch
L	Horizontal force on the shank
mph	Miles per hour
N_0	Normal load on cutting tool
n	Number of sets
o	Degree
P_H	Horizontal force on hitch (draft)
psi	Pounds per square inch
P_V	Vertical force on hitch
P_{Vabs}	Absolute value of vertical force on hitch
P_{Vst}	Static force on hitch
r	Correlation coefficient
r^2	Coefficient of determination

R.R.	Rolling resistance
Rep.	Replicate
sec	Second
V	Vertical force on the shank
vs.	Versus
W_d	Bulk density
W_R	Wheel reaction
W_W	Wet unit weight
W	Total weight
w	Moisture percentage
ω	Angular velocity
δ	Lift angle of cutting tools
μ'	Coefficient of soil-metal friction
ρ	Coefficient of rolling resistance

Chapter 1

INTRODUCTION

An implement or a tool operating in the soil represents a complex system. Prediction of the system's behavior and performance is difficult because a large number of variables are involved in tilling the soil (a major component of the system). Further, to study the behavior of an implement under dynamic conditions, the relation between forces applied to the soil and the resultant soil reaction should be established.

Early research was based on the trial and error method. Sound knowledge of soil mechanics was lacking. With increased development in the knowledge of soil mechanics, research on the reactions caused by mechanical forces applied directly to the soil progressed. Many researchers tried to establish a soil-tool interaction system. Complex empirical and functional relationships of soil-tool systems developed to predict forces acting on a tool, however, the number of variables involved restricted their practical use. Other researchers attempted to formulate simplified equations using measurable soil parameters (Sirohi, 1967). Simplification increased primary limitations and the accuracy with which the soil parameters were measured showed greater probability of variation due to the measuring device and the manner of use. The cultivator chassis mechanics, investigated in this project, was not an exception to the above mentioned limitations. In the words of Gill and Vanden Berg (1967), "A partial mechanics can thus be both valid and useful if its limitations are known."

1.1 Historical Background of Soil Tillage and Cultivators

Tillage has been regarded as the first operation in agriculture. About twelve thousand years ago, land cultivation was started for food

and fiber (Wells, 1921). Tools were crude and made of stone and wooden pieces. Man had not learned to harness animals. Thousands of years passed without much development. Slowly and slowly man's sphere of knowledge started increasing through experience and observation. The need for more food and fiber necessitated the use of better tools.

According to the United States Bureau of the Census (1860) the original cultivator was, like the original plough, simply a hooked stick. This in time was developed into the hoe, and remained the common cultivating implement until the nineteenth century was well advanced. Tillage practices were categorized into primary and secondary phases and the cultivator was classed as a secondary tillage implement.

The depression of the 1930's was accompanied by a prolonged period of drought and high velocity winds causing soil drifting in the prairie regions of canada. This induced farmers and researchers to dry different implements and then select one - an answer to this problem. This search resulted in the development of the wide-blade cultivator. "The drive to mechanize grain farming was intensified in the 1940's,and this brought about noteworthy changes in equipment. The chisel plough, originally introduced as a deep tillage cultivator, was re-equipped with sweeps and was used as a heavy duty cultivator to replace the stiff-shank duck foot machine" (Anderson, 1967). Improvements have continued and today farmers can purchase several types of cultivators each designed for a different kind of field operation.

Looking into the reasons for adaptation, three factors were possibly responsible for the shift:

(a) Necessity for stubble mulch management,

(b) The limiting tendency of the tillage practice beyond which the extra investment (tilling the land) does not pay the equivalent return (yield of crop) (Baver, 1963),

(c) The lower draft requirement of cultivators in comparison to ploughs.

1.2 Purpose and Scope of this Study.

Two possible approaches appeared to be suitable to investigate the chassis mechanics of a cultivator. First, evaluation of parameters (mechanical, soil, others) under controlled laboratory conditions; second, testing the chassis mechanics out in the field. Available information on field testing was limited, therefore the latter approach was selected for investigation. The study was designed to investigate the following:

(i) Study of the forces acting on the chassis,

(ii) Chassis force balance under dynamic conditions.

Transducers were designed and fabricated to sense the forces and reactions on the cultivator chassis. Effect of operational depth, speed, bulk density and daily moisture percentage variation of the test plot, and the type of cutting unit on the chassis forces were investigated.

Limitations and unavoidable assumptions were scrutinized before proceeding with the investigation. Despite limitations in the field test techniques, it was felt that the investigation would provide valuable knowledge for agricultural engineers engaged in farm machinery research.

Chapter 2

REVIEW OF LITERATURE

"Engineering aims at supplying the farmers with as good as priceworthy tools and machines as possible. If the designer considers how these two requirements are to be met, his reflection will always begin with the forces acting on the machine components. The quality, durability, and priceworthiness will depend on the degree to which it has been possible to make it resistant to these forces." These words spoken by Kloth (1936) are still valid today.

2.1 Components of a Tillage Implement

Trailed type implements receiving support through their wheels have three bearing units: cutting, transport, and hitch. Ploughs and cultivators have much in common in terms of the number of forces acting on the bearing units in three planes. A basic difference existing between the two is the absence of side force from the cultivator bearing units.

The review of literature presented here has tried to cover only the developments and research which pertain to this investigation.

2.1.1 Cutting unit.

Nichols and Reed (1934) observed the fundamental characteristics of the action of mouldboard ploughs and found a phenomenon of repeated failure of soil by shear. Formation of a wedge ahead of the shear point, development of primary and secondary planes, and subsequent upward lifting of the soil block are the causes of shear failure.

Clyde (1937, 1944) pioneered much of the early research in measuring forces on tillage tools. A tillage meter was used to measure the six forces required to restrain the six degrees of freedom of a

cutting unit. The restraining forces were vectorially combined to locate the line of action of the resultant force acting on the cutting unit. The resultant force (total soil effect) studied was assumed to consist of components perpendicular to the surface, frictional force in the direction of soil movement, friction drag on the underside of the cutting unit, if any, and rolling resistance of wheels. However, the location of any one component was not evaluated and an attempt to determine the combination of forces causing the total effect on the cutting unit was not done. Field tests indicated that the value of the resultant force was variable for the same depth and speed.

Soehne (1956) analysed tillage action and arrived at the conclusion that four simple behavior equations can describe the soil tool system: soil-metal friction, shear failure, acceleration force for each block of soil, and cutting resistance. A primary assumption was that the forces acting on a tool took place on a stationary plane. Equilibrium conditions were assumed to develop mathematical equations to evaluate draft and vertical force on an inclined plane tool.

Kawamura (1957) used yielding by shear as a behavior criterion to develop the mechanics. Coulomb's equation was used to represent this criterion:

$$\tau = C + \sigma \tan \phi$$

where C = cohesion,

ϕ = angle of internal friction,

σ = normal stress, and

τ = shear stress

Total shear stress on the failure surface was calculated by considering the mass of the soil, the shear failure stress (ignoring the magnitude

of the normal stress), and the weight of the soil. Equilibrium conditions then permitted determination of the draft component. A simple inclined tool operating at various depths and lift angles (angle of inclination) showed that a minimum value of the draft occurs at a lift angle of about 25° for shallow operating depths and about 15° for deeper operating depths.

Payne's (1956) investigation and development of the mechanics to calculate the draft force was based on two behavior equations: soil failure by shear, and soil-metal friction. The concept of wedge formation (Figure 1) was used to explain the system and forces acting on a simple inclined tool (Figure 2). From equilibrium conditions of forces acting on the tool, two equations were used to predict the draft and vertical force:

$$D_R \cos \delta = B_C \cos \tau + B_R \sin (\phi + \tau) + T \cos \theta_M$$

$$+ 2 [S_R \cos \theta \sin (\alpha + \lambda) + S_C \cos \beta \cos \lambda] \quad \ldots\ldots\ldots\ldots (2)$$

$$W + D_R \sin \delta + D_A + B_C \sin \tau = T \sin \theta_M$$

$$+ 2 [S_R \sin \theta + S_C \sin \beta] \quad \ldots\ldots\ldots\ldots (3)$$

where

D_A = adhesion force acting on the tool,

D_R = resultant of normal and frictional forces acting on the back side of the wedge,

B_C = cohesive force (acting at the bottom surface of the wedge),

δ = angle of soil-metal friction,

B_R = resultant of normal and frictional forces (acting on the bottom surface of the wedge),

ϕ = angle of internal friction,

$(\phi + \tau)$ = inclination of B_R to the vertical direction,

S_C = cohesive force acting on the side of the wedge,

λ = angle between the direction of travel and the projection of S_C in a horizontal plane,

β = angle between horizontal plane and B_C,

S_R = resultant of normal and frictional forces acting on the side of the wedge,

T = force resulting from the shear failure of the two fronts (Figure 1) and acting on the leading edge of the wedge,

θ_M = direction of T from the direction of travel,

θ = angle S_R makes with the horizontal plane,

α = angle between the normal to the side of the wedge and the horizontal projection of S_R in the horizontal plane,

W = weight of the wedge.

The angles δ and ϕ are dynamic soil parameters that can be measured but the remaining unknown parameters must be determined from other relations. Cos δ D_R (equation 2) was the draft of the cutting unit.

A mechanics of pure cutting which did not consider any major failures other than separation of soil from the tool was developed and tested by Kostritsyn (1956). The draft equation developed by Kostritsyn was:

$$P = P_1 + P_2 + P_3 \qquad (4)$$

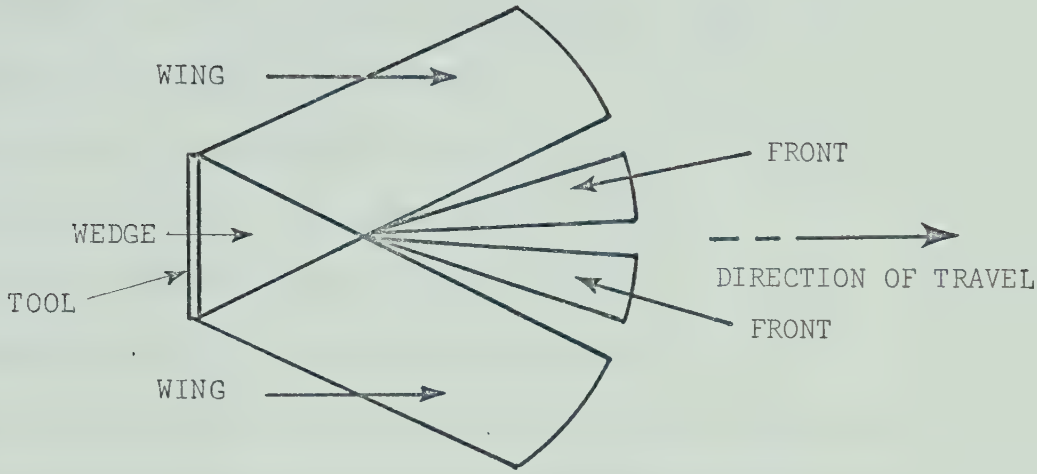
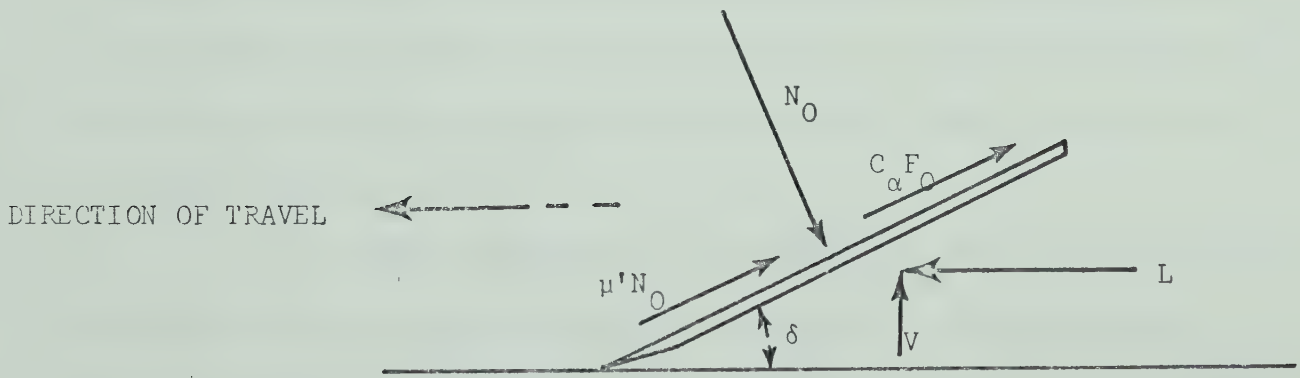


Figure 1: The nature of soil failure for soil reaction to a narrow vertical tillage tool.



δ - Lift angle of the tool,
N_O - Normal load,
F_O - Area of inclined tool,
C_α - Soil-metal adhesion,
μ' - Coefficient of soil-metal friction.

Figure 2: Free body diagram showing forces acting on a simple cutting tool.

where

P = total draft on the cutter,

P_1 = component of resistance resulting from the normal force on the wedge of the cutter,

P_2 = component of resistance resulting from the tangential force on the wedge of the cutter,

P_3 = component of resistance resulting from the tangential force on the side of the cutter.

Kaburaki (1959) studied a tool representing a half sweep. The data from these tests were used to predict the influence of lift angle, included angle, width of cut, width and depth ratio, and tool speed on the draft.

Dransfield et al.(1964) extended the work of Payne and studied the effect of rake angle, bulk density, moisture content, and speed on the soil-tool system. Field tests indicated that the magnitude of vertical force and draft was reasonably constant for the same functional parameters while the magnitude of vertical force changed considerably in compacted soil.

Reaves (1968) investigated the feasibility of similitude technique in performance studies of soil-chisel systems. A distorted model system was used and tested in a wide range of soils and soil conditions. A relationship between distortion and prediction factor was established empirically to predict the performance of a prototype.

Sirohi (1967) applied the technique of Reaves to study different sweep design and operational parameters. The draft was expressed as a function of:

$$D = f(v,g,h,l,p,w,\alpha,\beta)$$

where

D = draft,

v = velocity,

g = acceleration due to gravity,

h = operational sweep depth,

l = bulk volume weight,

p = resistance of soil penetration,

w = width of sweep,

α = approach angle of sweep,

β lift angle of sweep.

Six independent pi terms were selected and studied to predict sweep performance. Field tests were conducted to permit evaluation of four different types of relations: draft as a function of width at constant values of α and β, draft as a function of β at constant values of width and α, and draft as a function of operational variables h and w. Tests indicated that the minimum draft occurs at sweep sliding angles between 12 and 16 degrees. The horizontal component of the frictional force was 20% of the total draft and the normal force on the surface of the sweep was a function of the vertical and horizontal forces.

Luth and Wismer (1969) applied dimensional analysis techniques to analyse the soil-blade system. Variables were:

F_X = horizontal component of blade reaction, F

F_Z = vertical component of blade reaction, F

η = blade length, L

b = blade width, L

Z = blade operating depth, L

α = blade angle, (radians)

v = operating velocity, LT^{-1}

Y = unit weight, FL^{-3}

μ = coefficient of soil-metal friction,

ϕ = internal friction angle of soil,

g = acceleration due to gravity, LT^{-2}

The resulting prediction equations were:

$$\frac{F_x}{\gamma b z^{.5} \ell^{1.5}} = [1.05(\frac{z}{b})^{1.10} + 1.26 \frac{v^2}{g\ell} + 3.91]\ \alpha^{1.73}(\frac{z}{\ell \sin \alpha})^{.77} \quad . . . . . (5)$$

$$\frac{F_z}{\gamma b z^{0.5} \ell^{1.5}} = [1.93 - (\alpha - .714)^2](\frac{z}{\ell \sin \alpha})^{.777}$$

$$[1.31(\frac{z}{b})^{.966} + 1.43 \frac{v^2}{g\ell} + 5.605] \quad . . . . (6)$$

The equation for vertical force indicated that blade angles less than 65° from the horizontal resulted in a downward vertical reaction and angles greater than 65° from the horizontal resulted in an upward vertical reaction. Tests were conducted with artificial soils under controlled laboratory conditions. Standard error of estimate expressed as a percentage of the mean was thirteen percent for vertical and horizontal forces.

Fornstrom et al (1970) in a new approach to the application of soil mechanics, developed a set of phenomenological equations assuming that the tillage tool interaction with a bounded soil is a nonequilibrium process. Field tests indicated that random force fluctuations have an autocorrelation and the process is an irreversible one having Gaussian distribution.

2.1.2 Transport wheel.

The transport wheel considered here operates off the road and the

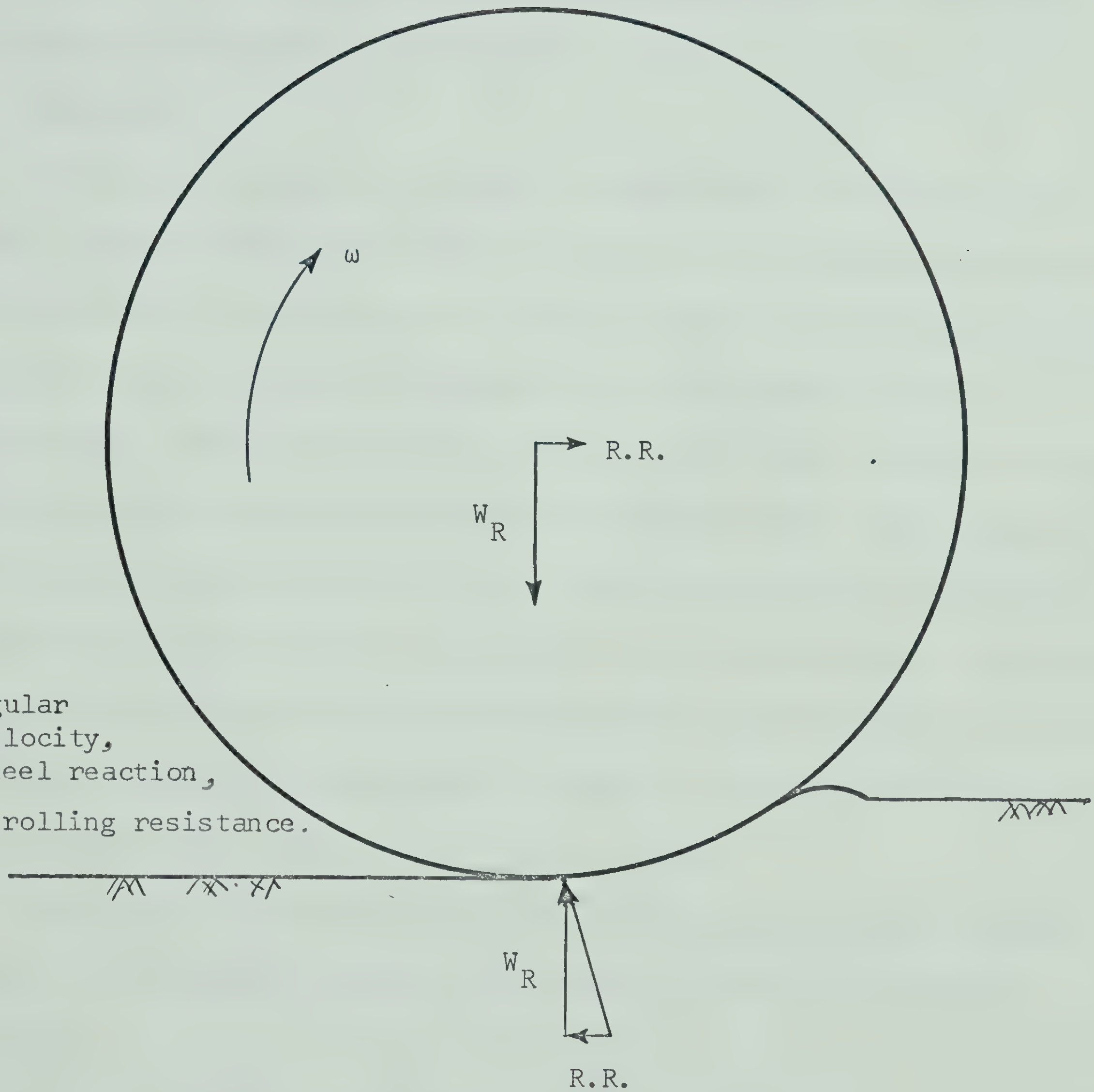
mechanics differs from a wheel operating on the road. On soft ground the wheel sinks in, and in effect continually tries to climb an incline. Torque input to the wheel is zero and the horizontal force acting on the axle of the wheel represents the force required to tow the device in the medium with the load carried (Gill and Vanden Berg, 1967). The reaction between the wheel and soil consists of elementary stresses in the contact area. These stresses having different magnitudes and directions can be added to represent a single soil reaction force (illustrated in Figure 3) as experienced by the wheel (Persson, 1967).

The resultant soil reaction force can be divided into vertical and horizontal components. The basic laws of mechanics states that the soil reaction force together with other forces acting on the wheel have to be in equilibrium. Therefore, the vertical component of the soil reaction force will balance the dynamic weight acting on the wheel and the horizontal component of soil reaction, the rolling resistance, will balance the force acting on the axle of the wheel.

2.1.3 Hitch link

When the tool is symmetrical sideways and the side forces are balanced, the weight of the implement which acts at the center of gravity, the pulling force which acts through the point of hitching, and total soil resistance on the tool are in the same plane and no couples are present (Clyde, 1935). For the cultivator, side forces are balanced, therefore the forces in the vertical plane only need to be considered in analysis (Clyde, 1970).

The hitch link of a cultivator (illustrated in Figure 14) is a system in itself. The forces acting under dynamic conditions must meet the requirements for equilibrium; the algebraic sum of the forces in any



ω - angular velocity,
W_R - wheel reaction,
R.R. - rolling resistance.

Figure 3: Transport wheel.

direction must be equal to zero. The two forces acting in the horizontal plane, pull exerted by the tractor drawbar, and total soil resistance supplied by the chassis must be equal and opposite. The dynamic part of the total weight of the cultivator acting at the hitch must be equal and opposite to the drawbar reaction.

2.2 Chassis

Systematic research on tillage implements was started by Clyde in 1934. Proper hitching and draft requirements of an implement were the main objectives. The forces acting on an implement were divided into four fundamental groups: weight of implement, pull, soil reaction, and inertia (Clyde, 1935). The inertia, which enters in when starting, stopping and striking obstructions, was neglected in uniform motion force analysis. Stable operation of an implement in the field indicated that the dynamic forces acting on the chassis, at any moment, are in equilibrium. Therefore, the three forces must meet the requirements for equilibrium and the sum of the forces in any one direction must be equal to zero. In addition the sum of the moments about a point must be equal to zero.

Field tests conducted at the Pennsylvania Agricultural Experiment Station by Clyde (1935) provided the following information on chassis mechanics:

(i) The forces on implements conform to the common laws of mechanics for equilibrium of forces in space.

(ii) The soil reaction on the working face and edge of sharp chisel-shaped tools apparently always has some downward components when the ground is moist. The effect of dry soil in this connection was not investigated.

(iii) A shorter and steeper hitch to the tractor would transfer more load from the plough axle to the tractor.

Bainer et al. (1955) provided a vector solution of a trailed type implement receiving vertical support only through wheels. The vector solution used Clyde's work to combine all forces (dynamic) and assumed uniform motion and equilibrium of the forces acting on the chassis.

Moller (1959) studied the draft requirements and working efficiencies of rigid and spring cultivator tines. The investigation was primarily concerned with the performance of tines in the field and did not provide much information on the forces (magnitude, direction) acting on a chassis. The draft requirements of rigid and spring tines in different soil and soil conditions were studied thoroughly and tested in the field to evaluate the effect of vibration on the working efficiencies of tines.

Coleman (1969) suggested that the weight transfer from implement to tractor on rigid frame tillage tools such as a field cultivator depends on the dominant term $\frac{h_1}{d_1}(P)$:

where h_1 = height of hitch above line of action of horizontal soil force,

d_1 = horizontal distance from hitch point to transport wheel ground contact,

P = draft.

The term was obtained by taking moments about the point of the transport wheel ground contact and equilibrium conditions were assumed to exist for stable operation of an implement.

The forces acting on a chassis (illustrated in Figure 4) obey the equilibrium laws and the sum of forces in any one direction must be

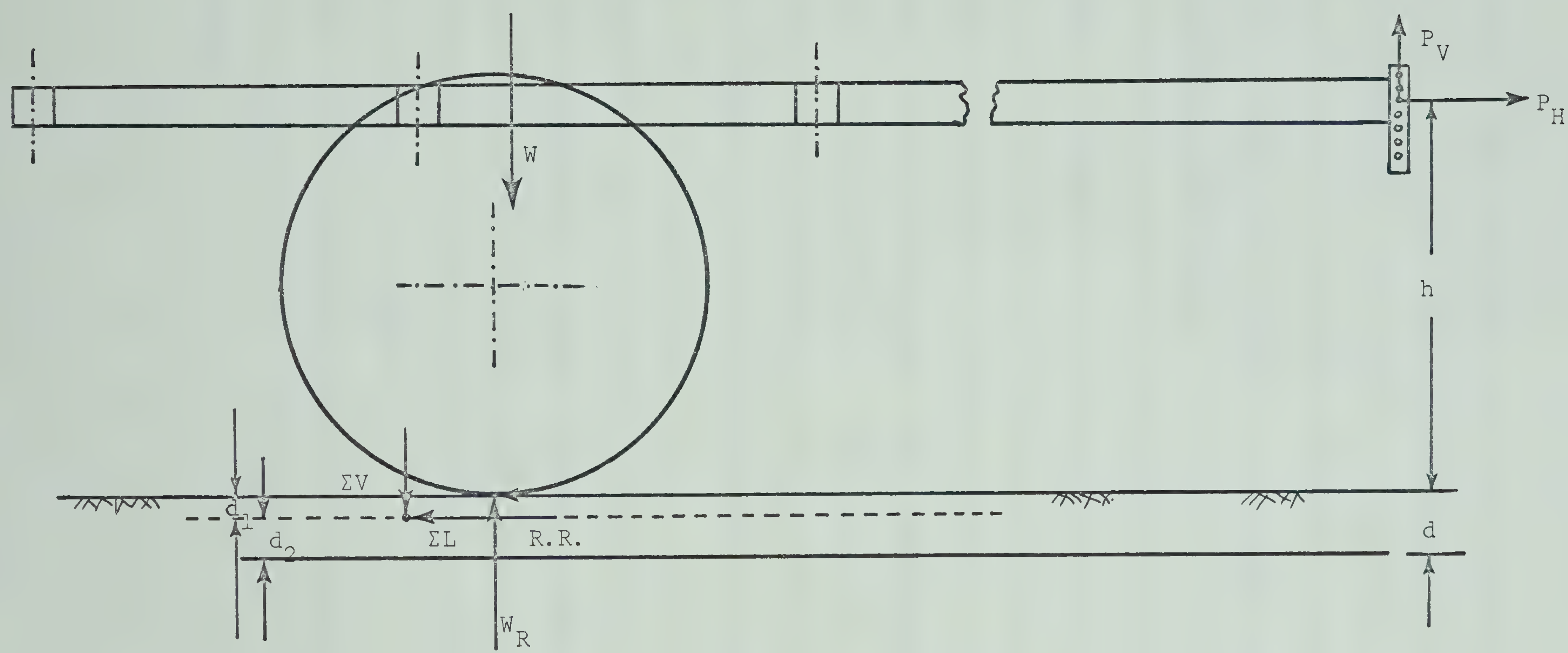


Figure 4:, Free body diagram of the cultivator showing forces acting in the vertical plane.

equal to zero. A cultivator has no side force and hence, the problem is reduced to a planar force analysis. Working with a cultivator having many cutting units, the total soil effect (resultant soil reaction) can replace all the reaction components and the line of action of the resultant soil reaction can be obtained experimentally.

2.3 Discussion on Literature

Development of mechanics, investigation,and field tests cited in the review of literature are the examples presently available which give some insight to the problem. "The partial mechanics used in the past studies is restricted and occasionally based on questionable assumptions" (Gill and Vanden Berg, 1967). Shortcomings in the past studies do not detract from the fine effort made by the researchers. In fact, the analytical approaches have demonstrated the use of mathematical treatments and equilibrium analysis to develop a set of equations. These equations were tested in the field or laboratory to obtain approximate values of the forces acting on a tool.

Recent development of non-equilibrium processes as applied to tillage-tool interaction has provided another approach in the application of soil mechanics. More work and field tests are needed to increase the usefulness and scope of this approach.

Some of the data available from the past research are given here:

A. Data available from Clyde's (1935) investigation on cultivator shovels.

Table 2.1. Soil force on a sharp 2 in. shovel in Hagerstown heavy silt loam.

Test No.	Moisture Content	Depth in.	Draft (L) lb.	Vertical Force (V) lb.	V/L Ratio	Specific Gravity gm/cm^3
70	19.5	1.50	21.0	10.8	0.51	1.206
71	19.5	2.00	21.7	13.0	0.59	1.206
72	19.5	3.50	41.3	14.4	0.34	1.206
73	19.5	4.75	114.5	38.8	0.33	1.206
74	19.5	4.00	74.0	28.0	0.37	1.206
77	15.8	1.75	35.0	5.0	0.14	1.238
78	15.8	2.00	29.0	14.0	0.48	1.238
79	15.8	2.75	40.0	9.6	0.24	1.238
80	15.8	3.75	72.0	21.8	0.30	1.238
81	15.8	4.00	91.8	31.3	0.34	1.238
82	15.8	5.00	108.0	32.5	0.30	1.238

Note:

(i) Information about the speed of test cultivator was not provided.

(ii) Forces (L,V) were based on the average of seven similar shovels.

B. Data obtained from Sirohi's (1967) investigation.

Table 2.2. Effect of speed on vertical force, draft, and V/L ratio at constant depth and soil (sand) parameters.

Sweep No.	Speed mph	Vertical Force (V) lb.	Draft (L) lb.	V/L Ratio
1	1.5	12.5	30.0	0.42
	2.0	12.0	30.5	0.39
	3.0	14.0	32.0	0.44
	4.0	15.0	36.0	0.42
	4.5	13.5	37.0	0.36
2	1.5	6.0	32.0	0.19
	3.0	8.5	42.0	0.20
	4.5	10.0	45.0	0.22
3	1.5	23.0	41.5	0.55
	3.0	24.5	46.0	0.53
	4.5	25.5	50.5	0.50
4	1.5	24.0	71.0	0.34
	3.0	33.5	67.5	0.50
	4.5	34.0	68.0	0.50

Table 2.3. Effect of depth and speed on vertical force, draft, and V/L ratio on sweep No. 1.

Speed mph	Depth in.	Vertical Force (V) lb.	Draft (L) lb.	V/L Ratio
2	2	24.0	45.0	0.53
	3	50.0	64.0	0.78
	4	68.0	85.0	0.80
4	2	24.0	46.0	0.52
	4	50.0	69.0	0.72
	6	73.0	99.0	0.74

Note: Data on other sweeps were not available.

Table 2.4. Information on sweeps mentioned in table 2.2 and 2.3.

Sweep No.	Sweep width in.	Sweep wing width in.	Sweep wing surface area, sq. in.	Lift height in.	Lift angle degree	Approach angle (included angle) degree	Soil slide angle degree	Sweep wing length in.
1	8.0	1.5	24.0	0.5	19.5	60	10.2	8.0
2	4.0	1.5	12.0	0.5	19.5	60	10.2	4.0
3	12.0	1.5	36.0	0.5	19.5	60	10.2	12.0
4	16.0	1.5	48.0	0.5	19.5	60	10.2	16.0

Chapter 3

EXPERIMENTAL PROCEDURE

3.1 Pertinent Variables Selected for Study

The selection of variables of a physical system was an important decision. The two major factors governing this decision were:

1. the difficulties in practicing control measures in the field,
2. the validity of results.

Considering these factors, the variables studied were:

(a) Soil (i) moisture content,
(ii) bulk density,

(b) Others (i) operational depth,
(ii) operational speed,
(iii) type of cutting unit.

3.2 Equipment

3.2.1 Equipment used to measure forces on the chassis.

Forces acting on the chassis were:

(a) draft (P_H),

(b) vertical force acting on the hitch (P_V),

(c) wheel reaction (W_R),

(d) horizontal force acting on individual cutting unit (L),

(e) vertical force acting on individual cutting unit (V),

(f) rolling resistance of the wheels (R.R.).

The equipment used in this study consisted of the following:

1. Test Cultivator: International Harvester Company 55 Chisel Plough 13-foot basic with two-foot extension equipped with 6.70-15 tires. Three types of cultivator shovels were used in the field tests. These were:

   (a) $15\frac{1}{2}$ in. high lift sweep,

   (b) 16 in. low lift sweep,

   (c) 2 in. chisel point.

   Additional information is given in Appendix A.

2. Pulling unit: International Harvester Company Farmall 756 diesel tractor equipped with 6.00-20 front tires and 15.5-38 rear tires.

3. Hitch force transducer: The transducer was designed to replace the hitch link and work as both a horizontal and vertical force transducer. Two strain gauge circuits (Wheatstone bridge type) were used to sense the two forces (draft and vertical) independently. Proper orientation and location of gauges helped to minimize the effect of undesirable forces (Appendix A).

4. Wheel reaction transducer: One of the original links joining the rockshaft and wheel brace was replaced by a transducer sensing dynamic weight acting on the wheel. The strain gauge circuit (Wheatstone bridge type) of the transducer was free from forces acting in any direction except the vertical (Appendix A).

5. Shank force transducer: The transducer was designed to sense the resultant force acting on a cutting unit. The ultimate object was to resolve the resultant force into

its vertical and horizontal components. Two possible approaches appeared to be suitable for this purpose. First, a shank could be redesigned and simplified such that the direct measurement of horizontal and vertical components of the resultant force acting on the shank is possible; second, two strain gauge circuits could be used at two different places on the original shank. Location of the two sets of gauges giving two different deflection values of the same resultant force (for equal amplification and galvanometer sensitivity) could be used to form simultaneous equations. Further, the simultaneous equations could be used to obtain the value of component forces. To simulate field use, the latter approach was selected for this project. The two axes selected on the shank for setting strain gauges were (a) maximum curvature and (b) horizontal portion. These locations are shown in Figure 5a.

6. Recording equipment: A 6-channel ultra-violet recording system, type SE.3006 (illustrated in Figure 6) was used to record forces sensed by the three transducers. The recording system consisted of a paper supply and control, circuit balance, amplifiers, filters, galvanometers, and ultra-violet recording units. The recording paper employed (Kodak Linagraph Direct Print Paper, 6 in. x 125 ft.) was light sensitive and produced visible traces when exposed to ultra-violet light.

7. Dillon dynamometer: Serial AN 1230, Capacity 2500 pounds.

The dynamometer was used to measure the rolling resistance of the cultivator in conjunction with an auxiliary unit. The auxiliary unit (Figure 5b) was fastened on the drawbar and served two purposes:

(a) A smooth sliding contact surface to provide flexibility in movement (lateral and longitudinal) of the cultivator hitch point.

(b) To keep dynamometer free from the effect of vertical force acting on the hitch.

8. Portable Power source: Kohler electric plant, Model 1.25 mm 25, Series 326386, 1800 rpm, 1250 watts, 120 volts at 60 cycles per second.

In addition to these pieces of equipment,a set of five fifty-foot shielded cables were used to connect five 5-pin male connectors to the recorder installed on a half ton truck. The truck was outfitted with a shade protection for the recorder and thus served as a mobile instrument vehicle (Figure 6).

3.2.2 Equipment used to measure soil parameters, depth, and speed.

1. Soil sampler: Small tin cans were used to keep soil samples for weighing and oven drying.

2. Core sampler: The core sampler used to measure bulk density of test plot consisted of two cylinders fitted one inside the other. The outer one extended above and below the inner to accept a hammer at the upper end and to form a cutting edge at the lower. The inside cylinder was the sample holder. The inside diameter of the two cylinders when nested were essentially the same at the

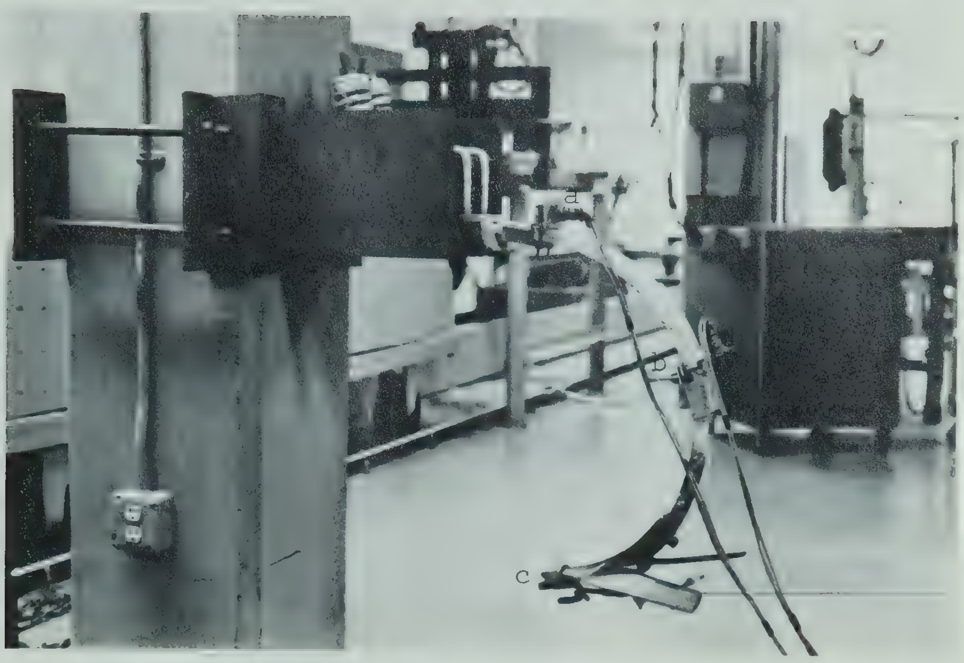


Figure 5a: Laboratory calibration of shank force transducer showing:
(a) Strain gauges on the horizontal portion of the shank,
(b) Strain gauges on maximum curvature of the shank, and
(c) Load applying device on the sweep.

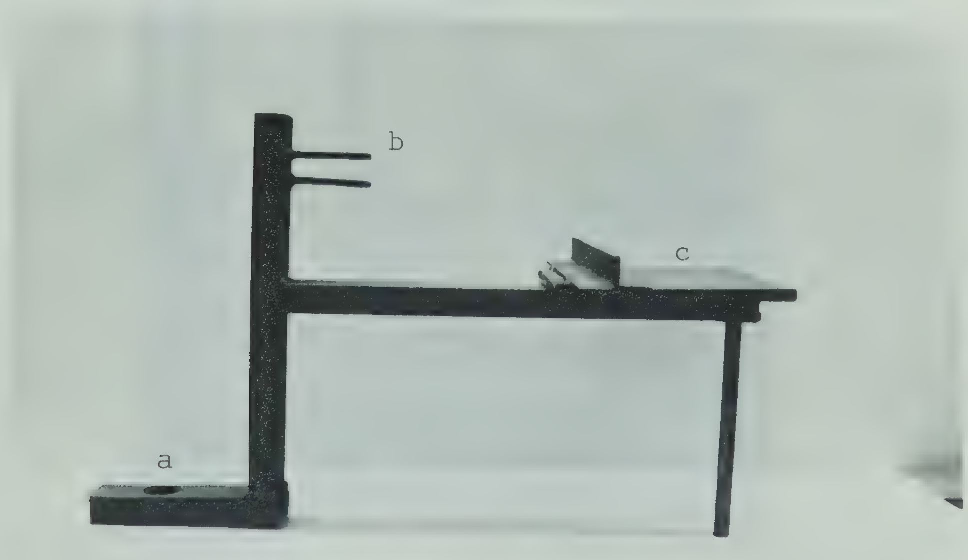


Figure 5b: A device used in rolling resistance measurement showing:
(a) drawbar connection
(b) dynamometer connection, and
(c) platform to support cultivator.

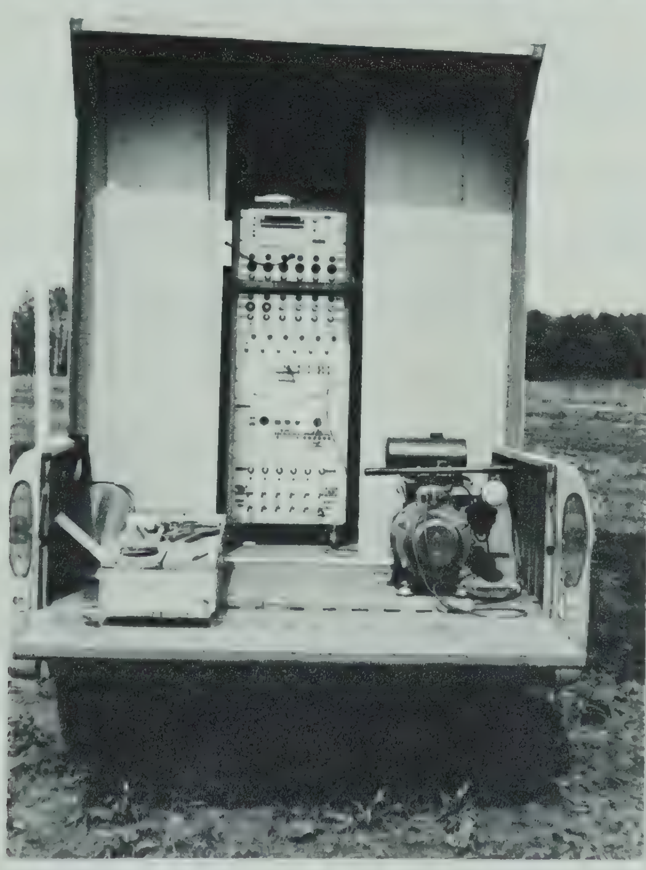


Figure 6 : Top - A general view of the instrumented cultivator, Bottom - Mobile instrument vehicle.

lower end, the inner being fitted against a shoulder cut on the inner surface of the outside cylinder.

3. Proving ring penetrometer: A proving ring penetrometer of the cone type was used to measure the penetration resistance of the test plot soil. The instrument consisted of a T-handle, one 18 inch penetration rod, one three foot extension rod graduated every six inches, one proving ring of 250 pounds capacity with dial indicator, and a removable cone point. The base area of the 30° circular stainless steel cone was 0.2 square inch.

4. Depth measuring instrument: A simple, handy and manually operated depth measuring device was fabricated in the Agricultural Engineering workshop of the University of Alberta. The instrument (Figure 7) consisted of (a) a rectangular iron plate (8 in. x 6 in. x ¼ in.) heavy enough to compact the cultivated portion of the soil to the original elevation when dropped from a set height for a definite number of times, (b) a 1 in. hole bored in the center of the plate and a pipe 4.5 ft. long and 1 in. diameter welded in the hole, and (c) an iron rod of 5/8 in. diameter, 6.5 ft. long used as a guide for the plate and pipe unit and as an indicator of depth in the field. The rod was marked in inches at the upper end.

5. Stopwatch: A stopwatch, readable up to 0.1 second, was used to record time taken by the cultivator to complete the 60 ft. run length.

Figure 7a : Depth measuring device.

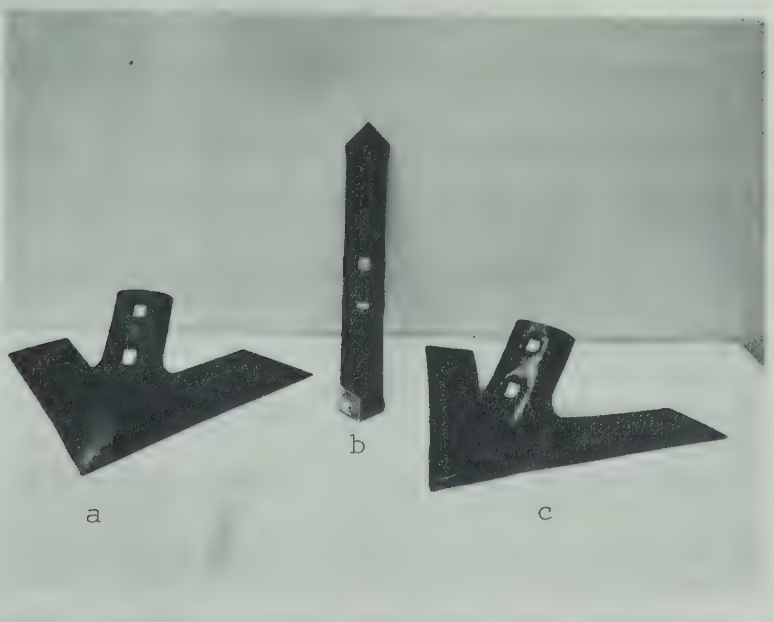


Figure 7b : Cutting units: (a) 15½ in. high lift sweep, (b) 2 in. chisel point, and (c) 16 in. low lift sweep.

6. Tape measure: A 100 ft. tape, readable up to 0.25 in., was used to measure the length of a run.

3.3 Calibration of Equipment

A. Ultra-violet recording system. The voltage supply to transducer circuits was maintained constant throughout the tests. A calibration resistor shunted across one arm of the bridge produced a simulated strain resulting in a certain galvanometer deflection on the recording paper. The galvanometer deflection for a constant voltage supply, was governed only by the type of galvanometer and amplification selected. To overcome drift a predetermined calibration deflection was selected for each circuit and maintained by amplifier adjustment.

B. Calibration of Transducers.

1. Hitch link transducer: The transducer, having two independent circuits for vertical and horizontal forces, was calibrated separately for each circuit. In the beginning of calibration, repeated vertical and horizontal loads were applied on the transducer to minimize the hysteresis effect.

(i) Vertical force circuit: In field operation there was virtually no vertical movement of the transducer attached to the drawbar of the tractor. To simulate field loading conditions, a test jig was constructed to keep the drawbar (yoke) end of the transducer fixed and allow vertical loading at the cultivator end. Both circuits (vertical and horizontal forces) were connected to the ultra-violet recorder and

load was applied by a Baldwin universal testing machine. Figure 8 shows the calibration curve obtained. The circuit for horizontal loading did not give any output for vertical load, and hence the circuit was free from the effect of vertical force acting on hitch link transducer in the field.

(ii) Horizontal force circuit: Horizontal (axial) loading condition was simulated with a fork having an inside clearance equal to the width of the transducer (cultivator end) and a flat iron piece equal in thickness of the drawbar of the tractor (drawbar connecting end of the transducer). Both circuits (horizontal and vertical forces) were connected to the recorder and axial load was applied by the Baldwin Universal testing machine. Figure 9 shows the calibration curve obtained. The circuit for vertical force also gave an output for horizontal loading. This indicated an error in orientation of gauges in the circuit. Figure 10 shows the curve obtained which was used in the data analysis to obtain the correct value of vertical force.

C. Wheel reaction transducer. The transducer was effective only for axial load. Two simple connectors were fabricated in the departmental workshop to simulate the field loading condition. The strain gauge circuit of the transducer was balanced and kept at a predetermined calibration deflection

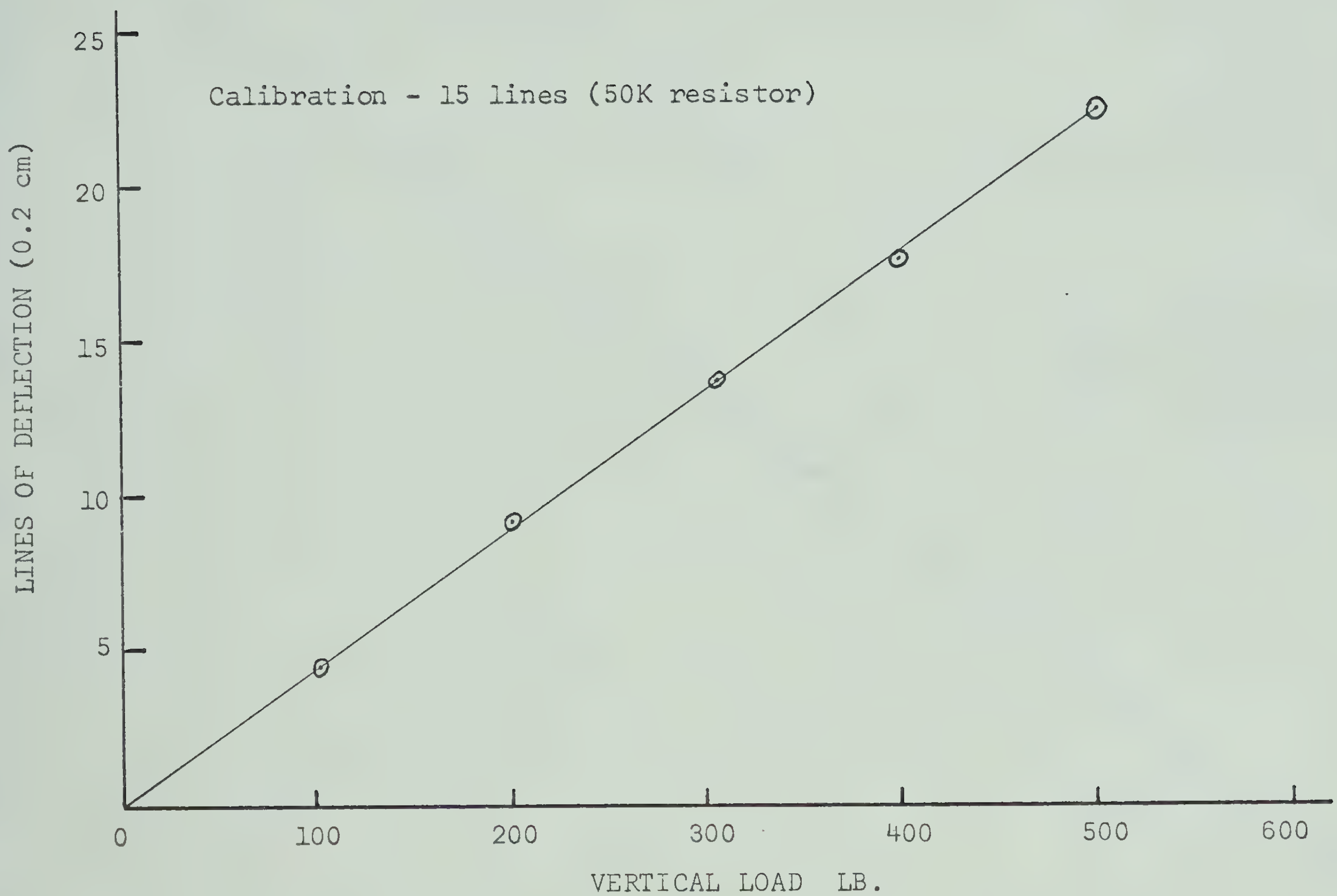


Figure 8: Calibration of hitch link transducer sensing vertical force.

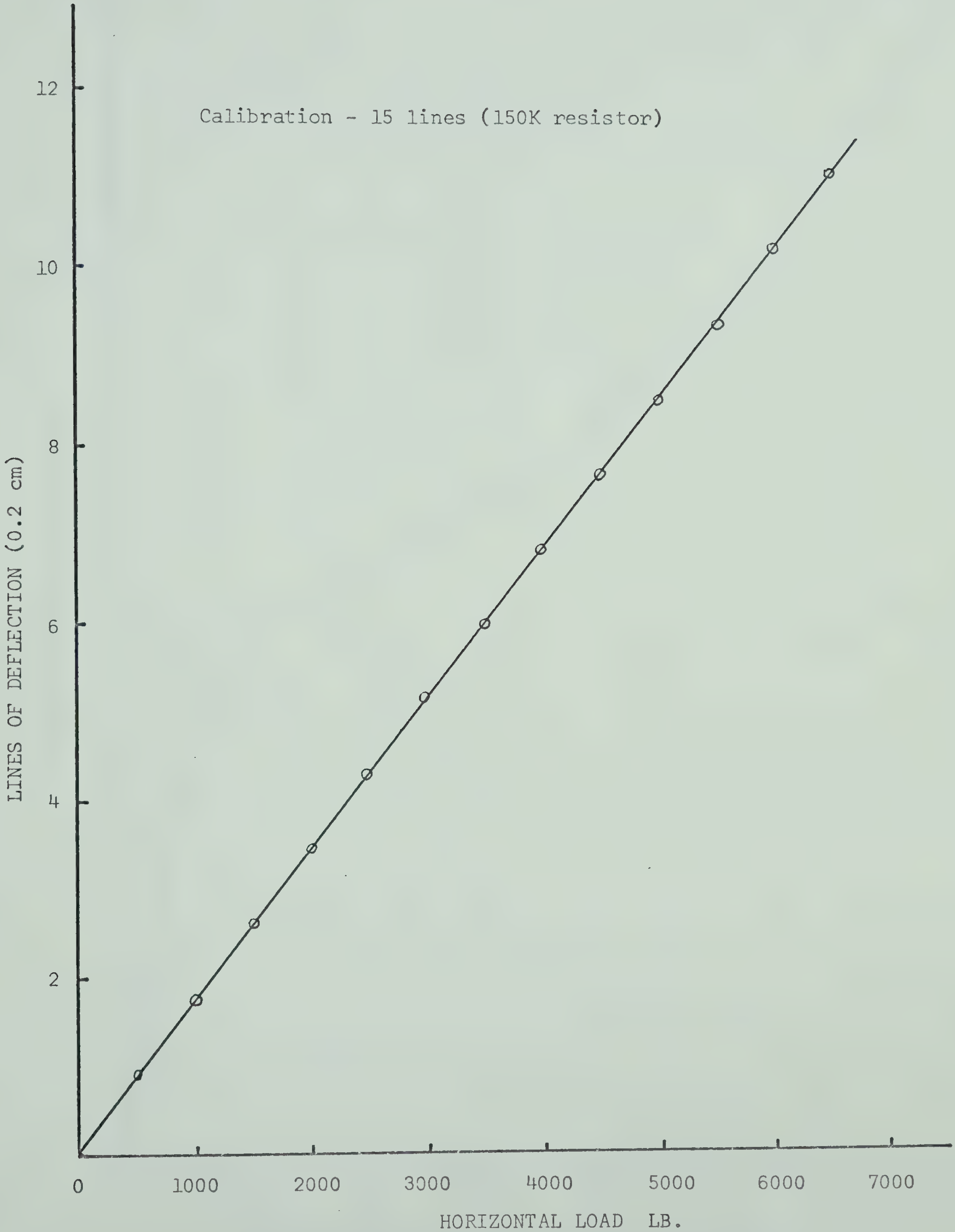


Figure 9: Calibration of hitch link transducer sensing horizontal load (draft).

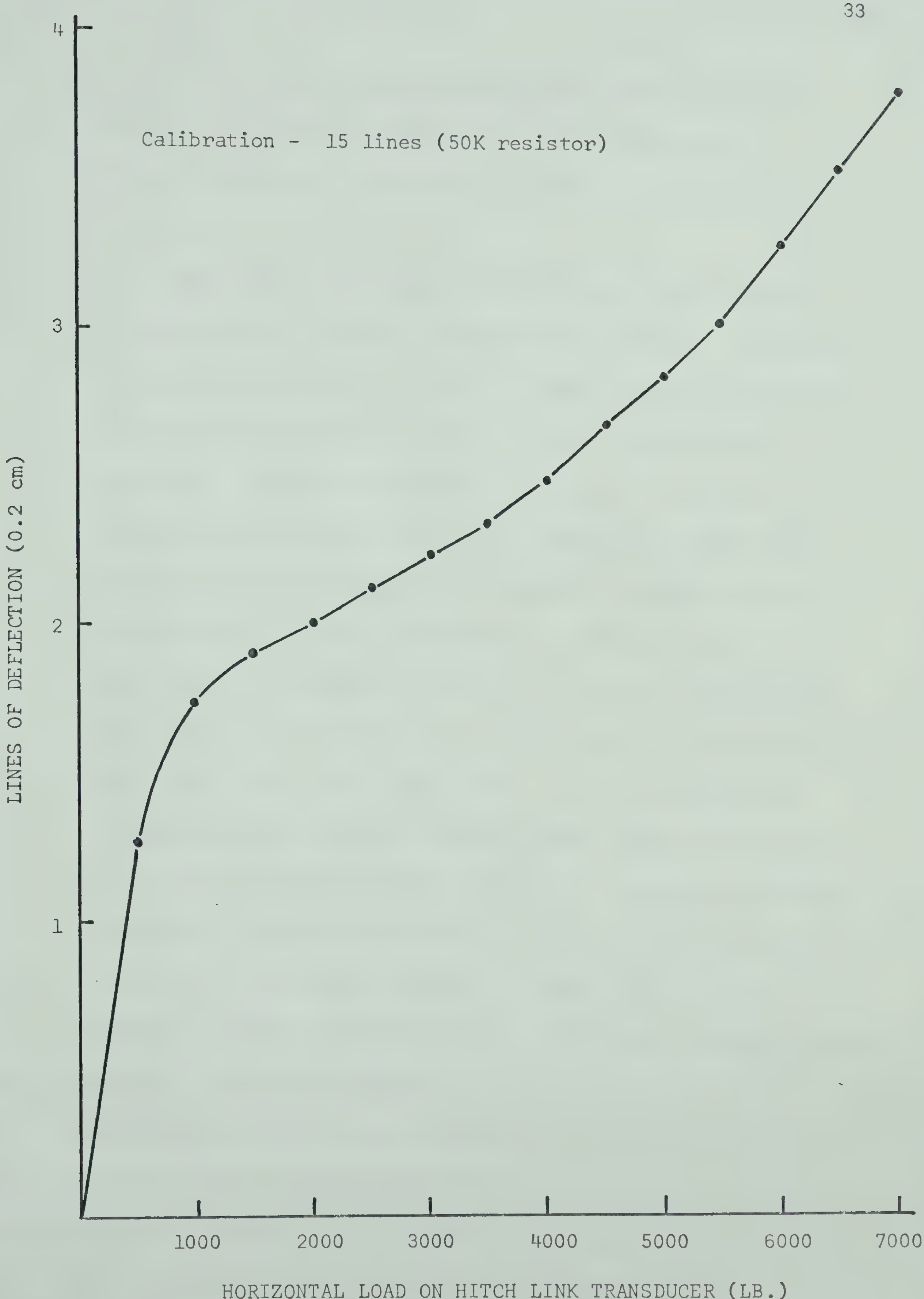


Figure 10: Correction curve for horizontal loading (draft) on vertical force (hitch link) transducer.

on the record chart. Load (tensile and compressive) was applied by the Baldwin Universal testing machine to obtain calibration curves which are shown in Figures 11 and 12.

D. <u>Shank force transducer.</u> The resultant force acting on the shank was sensed by two separate circuits. Simulation of field condition was modified to obtain separate calibration curves for horizontal and vertical forces acting on the transducer. Location of center of resistance to apply horizontal and vertical loads on the sweep was decided after considering Clyde's suggestion (obtained through personal communication), related literature, and advice of the supervisor. A hook, made to fit at the center of resistance of the sweep, was connected by a wire rope to a Dillon pull meter and a winch. The shank and sweep unit was placed on a square section similar to the cultivator frame and oriented in a manner to simulate either horizontal or vertical loading condition. Load was applied with the winch and read on the Dillon pull meter and as outputs of both circuits on the recorder. Figures 13a and 13b are the calibration curves obtained.

3.4 Preliminary Testing of Equipment

Preliminary testing of the transducers and the inability of the tractor to maintain the required maximum speed resulted in some modifications and changes in the recording procedure. These were:

1. The use of more sensitive galvanometers in draft and wheel reaction recording channels to increase the

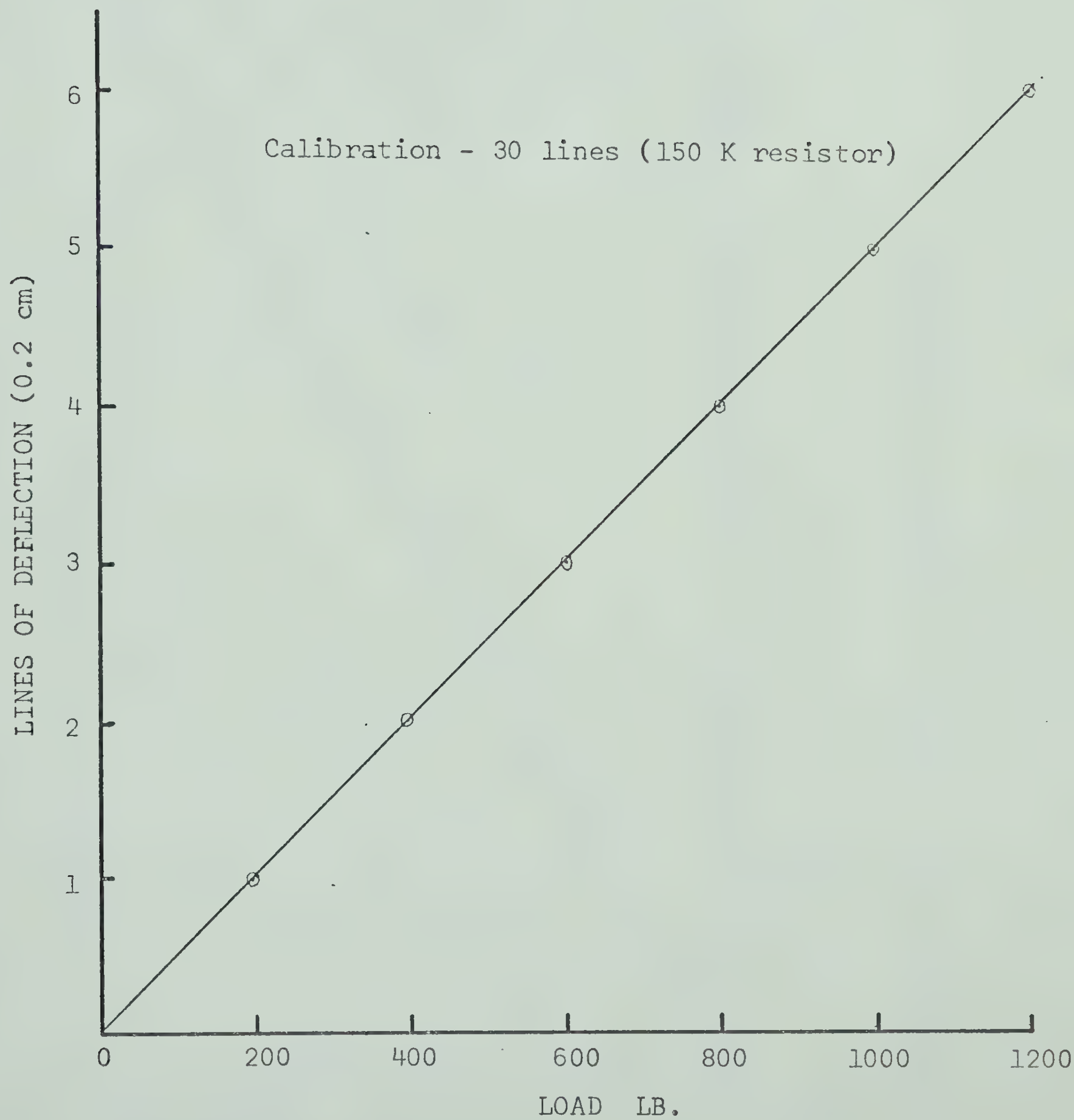


Figure 11: Calibration of wheel reaction transducer (compressive load).

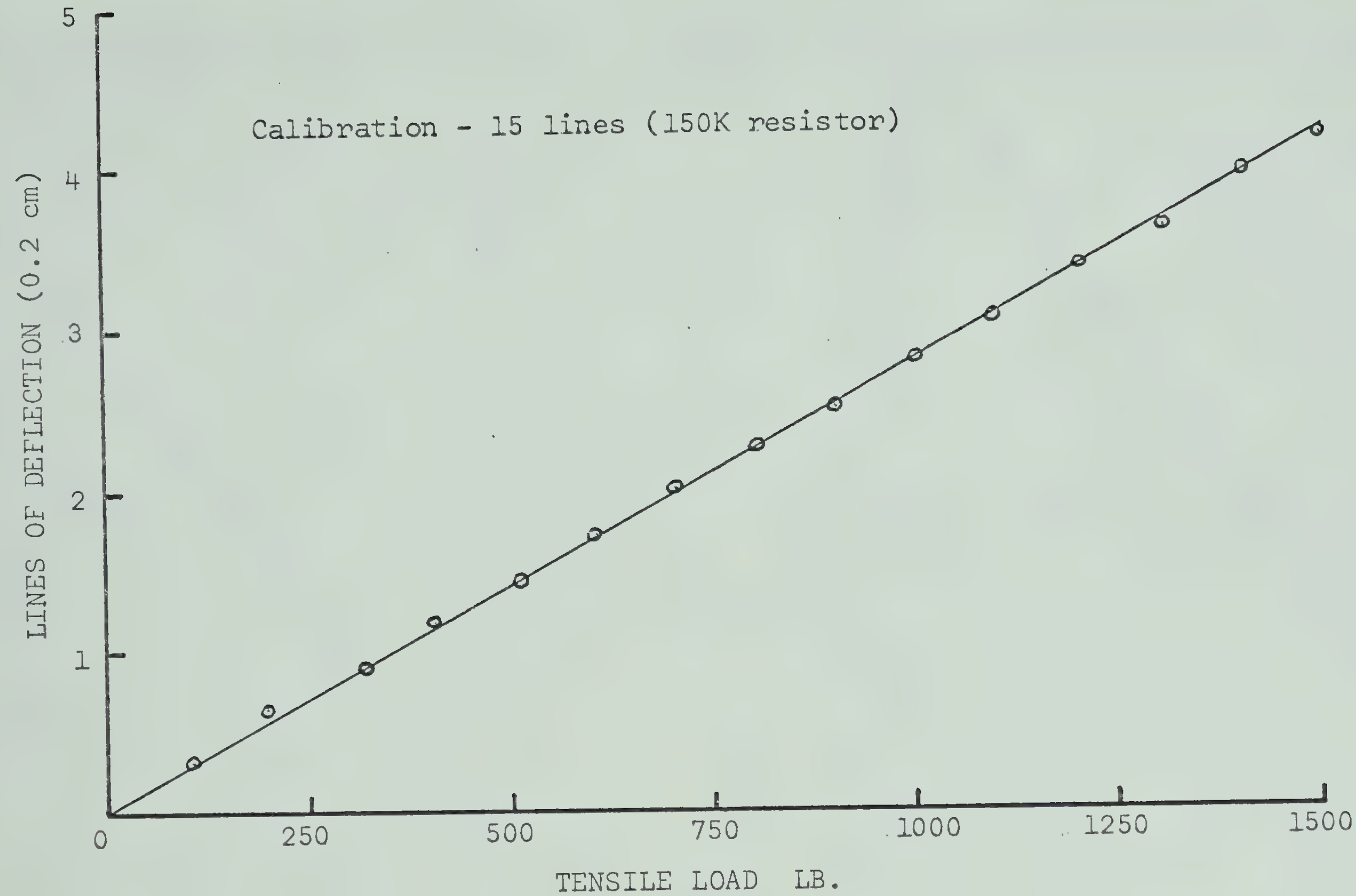


Figure 12: Calibration of wheel reaction transducer (tensile load).

Calibration of shank force transducer.

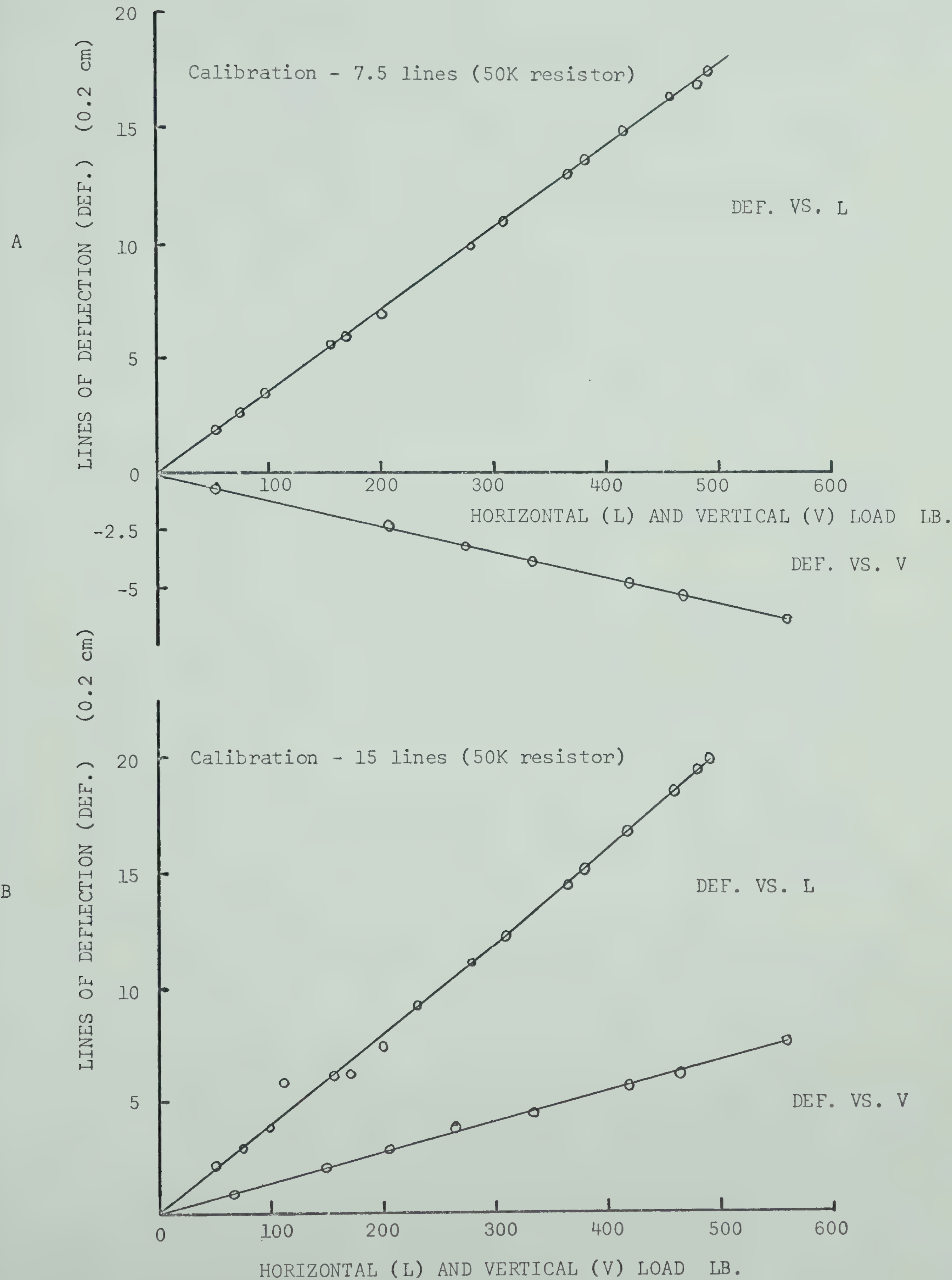


Figure 13: Top - Strain gauges on horizontal portion of shank,
Bottom - Strain gauges on maximum curvature of shank.

deflection capability for the same input voltage and amplification.

2. The provision for reversing the direction of signals, if required, to avoid interference among recorded signals.

3. Reduction in total number of shanks of the test cultivator (the tractor was not able to pull the cultivator with 13 shanks at maximum set speed and depth).

The measuring device, when tried out in the field, gave a good average value at a particular ram setting. The average depth value had good repeatability in similar conditions. A large number of trials and replications demanded a quick and reliable guide to switch from one known depth to another. The hydraulic ram of the cultivator was selected for this purpose and the setting for each depth was obtained in the laboratory. The ram setting was used as an indicator of depth in the field tests. For each depth the ram setting was adjusted accordingly by changing a clamp on the cylinder rod of the ram. The depth measuring device in fact measured the actual values of a set depth.

The remaining equipment did not require any changes and worked satisfactorily.

3.5 Field Test Procedure

A. Tests with 16-inch low lift sweeps in normal soil.

A typical field test was carried out as follows:

1. The tractor and portable generator were serviced for fuel and oil and checked for malfunctioning of the engines.

2. The portable generator was started and the amplifier sets of the recorder turned on at least 30 minutes before the beginning of data collection to allow warm-up and stabilization of amplifiers.

3. The test cultivator was positioned at the end of 60 ft. cables coming from the instrumentation truck.

4. A 60 ft. run length was measured along the side of cultivator and range poles were placed at both ends. Sufficient margin, in terms of distance, was given at the start of a run for the driver to adjust the tractor speed and to be ready to measure the time taken by the cultivator to cover this distance.

5. The transducers were connected to the recording equipment through five 5-pin connectors. All tranducers outputs were balanced, calibrated, zeroed, and positioned at specified positions on the recording paper.

6. The hydraulic ram was set for a predetermined depth.

7. The hitch link was connected to the cultivator in a predetermined hole (Figure 14) to correspond with the ram setting and keep the cultivator level in operation.

8. A chart speed of 12 inch per minute and a time-line interval of 1.0 second was selected and used for all runs.

9. Access to the recorder was closed completely and the tractor driver was instructed through a portable "walkie-talkie". In turn, the driver indicated when the cultivator was just passing the starting and finishing poles with respect to a fixed point on the cultivator.

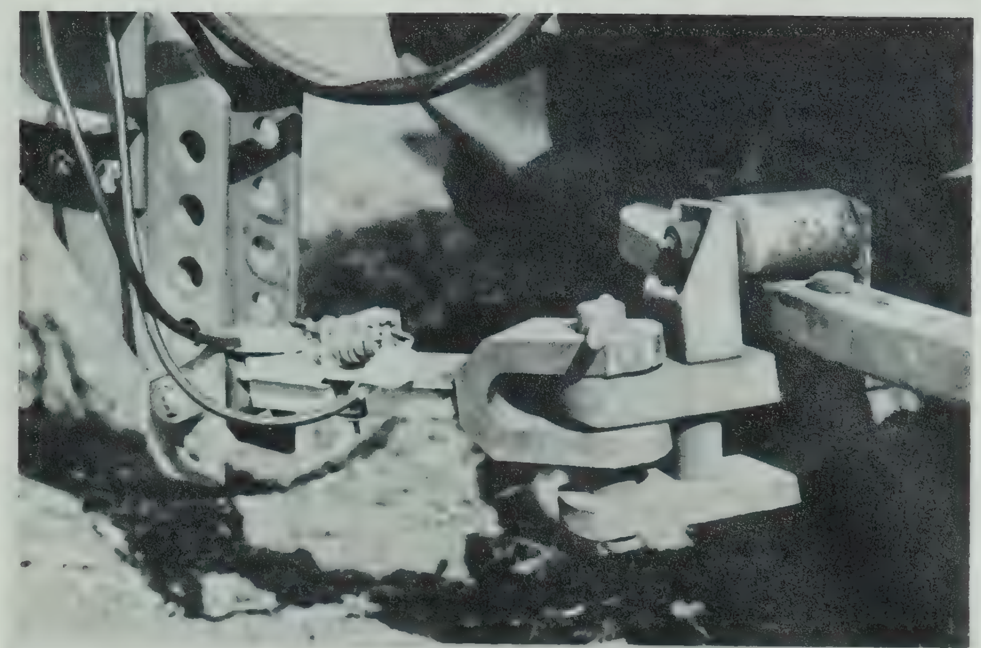


Figure 14: Top-Hitch link transducer in operation, Bottom-Wheel reaction transducer in operation.

10. The instrument truck was driven ahead and positioned at a suitable distance from the cultivator for the next run.
11. After visual inspection the record chart was rolled up, marked suitably for reference and cut off to be stored away from sunlight for proper chemical processing.
12. The depth at ten different places in two rows selected at random across the run length was measured and recorded for later use.
13. Soil samples were taken for moisture percentage determinations. A total of six samples were taken at two, four and six inch depths inside the test plot.

B. Tests with other sweeps and chisel points in normal and compacted soils.

Field testing basically followed the same procedure as described in A. A very high degree of fluctuation of signals was encountered in compacted soil. For these tests, the calibration deflections of the fluctuating signals were cut down to half, the location of signals were changed on the recording paper, and the direction of several signals were reversed. Despite these measures the signals were still intertwining with one another at higher depths and speeds. The compacted portion of the test plot was very limited in area and prohibited extensive trials. Consequently only 15.5 inch high lift sweeps and 2 inch chisel points were selected for trials.

3.6 Supplementary Tests

3.6.1 Location of center of gravity of the cultivator.

A. Three rows of shanks.

1. The location of vertical longitudinal plane, passing through the center of gravity, was obtained with the help of two platform balances placed under the two wheels of the cultivator. The cultivator frame was adjusted and levelled separately for simulated depths of two, four and six inches, and for the maximum raised position with respect to the cultivator wheels. The balances' readings were recorded for each setting. By taking the moments about one wheel, the location of the plane was obtained.

2. To obtain the location of a vertical line passing through the center of gravity of the cultivator, a platform balance was placed under the hitch. The chassis was levelled again at the standard drawbar heights used in field trials. The static weight acting on the wheels and the hitch were recorded for calculation purposes.

B. Location of the center of gravity of the following combinations of rows.

(a) First row of shanks,

(b) Second row of shanks,

(c) Third row of shanks,

(d) First and second rows of shanks,

(e) First and third rows of shanks,

(f) Second and third rows of shanks.

Measurement and calculation of center of gravity of the

above combinations followed the same procedure as described in A.

3.6.2 Measurement of soil parameters.

A. Moisture content: Samples collected in soil samplers (small tin cans), about 100 gm. in weight, were weighed and dried in an oven at 104°C for 24 hours. The dry weight of each sample and tare weight of the sampler were noted on a data sheet. The formula used to calculate the moisture content of the soil samples was:

$$\text{water content } (w) = \frac{\text{weight of water}}{\text{weight of dry soil}} \times 100 \; . \; . \; . \; . \; . \; (7)$$

B. Bulk Density: The core sampler was driven into a horizontal soil surface (selected prior to taking the sample) far enough to fill the sampler, but not so far as to compress the soil in the confined space of the sampler. The sample was carefully removed to preserve the natural structure of the soil. The inside cylinder containing the sample was removed from the outer cover and the soil extending beyond each end of the sample holder was trimmed level with the holder. The inside volume of the sample holder had been established previously and hence, the sample volume was considered the same in bulk density calculations. The water content determination followed the procedure as described in 3.6.2-A. The bulk density was calculated by the following formula:

$$W_d = \frac{W_w}{1 + \frac{w}{100}} \; . \; (8)$$

where W_d = bulk density (dry basis), $\frac{gm}{cc}$,

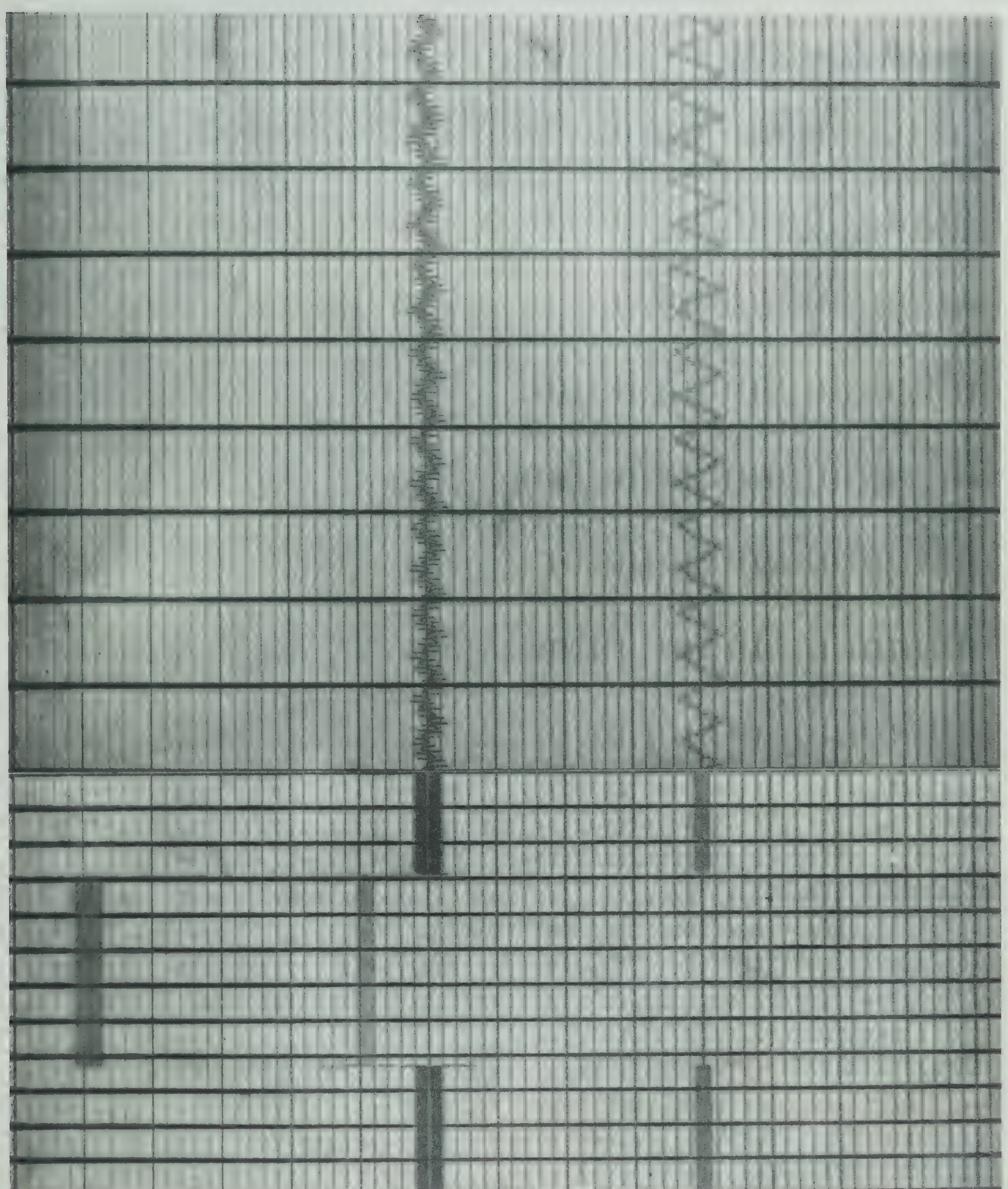
W_w = wet unit weight of a sample, $\frac{gm}{cc}$,

w = percent of moisture (dry basis).

The bulk density for both normal and compacted soils of the test plot was obtained four times during the fifty days of data collection. Each time a total of ten random samples were collected for both normal and compacted soils. The data are included in Appendix B.

3.6.3 Frequency measurement of the shank force transducer.

The test setup was prepared in the departmental laboratory. The transducer was placed on the frame used previously for calibration purposes and clamped tightly by U-bolts. The two circuits of the transducer were connected to the recorder and amplification and paper speed were adjusted to give clear and high peaks of vibration. A momentary force (at the center of resistance) was applied separately in the horizontal and vertical direcitons, and at an angle to the sweep. Signals coming from the two circuits were recorded on a chart and stored away from light for proper chemical processing. Particular attention was given not to excite other modes. The dominant frequency (20 cycles per second) was obtained by counting the number of cycles of disturbance per second on the processed chart (illustrated in Figure 15).



$\frac{1}{10}$ sec.

C H

Figure 15: Record chart showing: Top-Frequency of shank force transducer, Bottom-Zero load calibration of two signals (H,C) coming from the same transducer.

Chapter 4

RESULTS AND DISCUSSION

4.1 Analysis of Data

Record charts from the ultra-violet recorder were processed chemically in the departmental laboratory. The zero location of the signals (amplifiers outputs) and calibration deflections were included in each chart as reference. Figure 16 shows a photographic copy of an analog data sheet.

Analysis of a typical chart was as follows:

1. The chart was visually inspected to detect any error in recording or processing. The length of chart selected for analysis varied according to the depth and speed of a test run.
2. The area confined between the zero line and recorded signal (a center line was drawn through those deflection signals whose width was large (1-2 lines) due to a-c ripple) was measured by a planimeter. Subsequently the area was converted into average lines (0.2 cm) of deflection for each signal.
3. A correction was applied to the vertical force deflection value to take into account the effect due to the horizontal force.
4. The response (in terms of deflection) of the two sets of gauges on the shank force transducer was the resultant soil effect. This was divided into vertical and horizontal components with the help of two simultaneous equations.

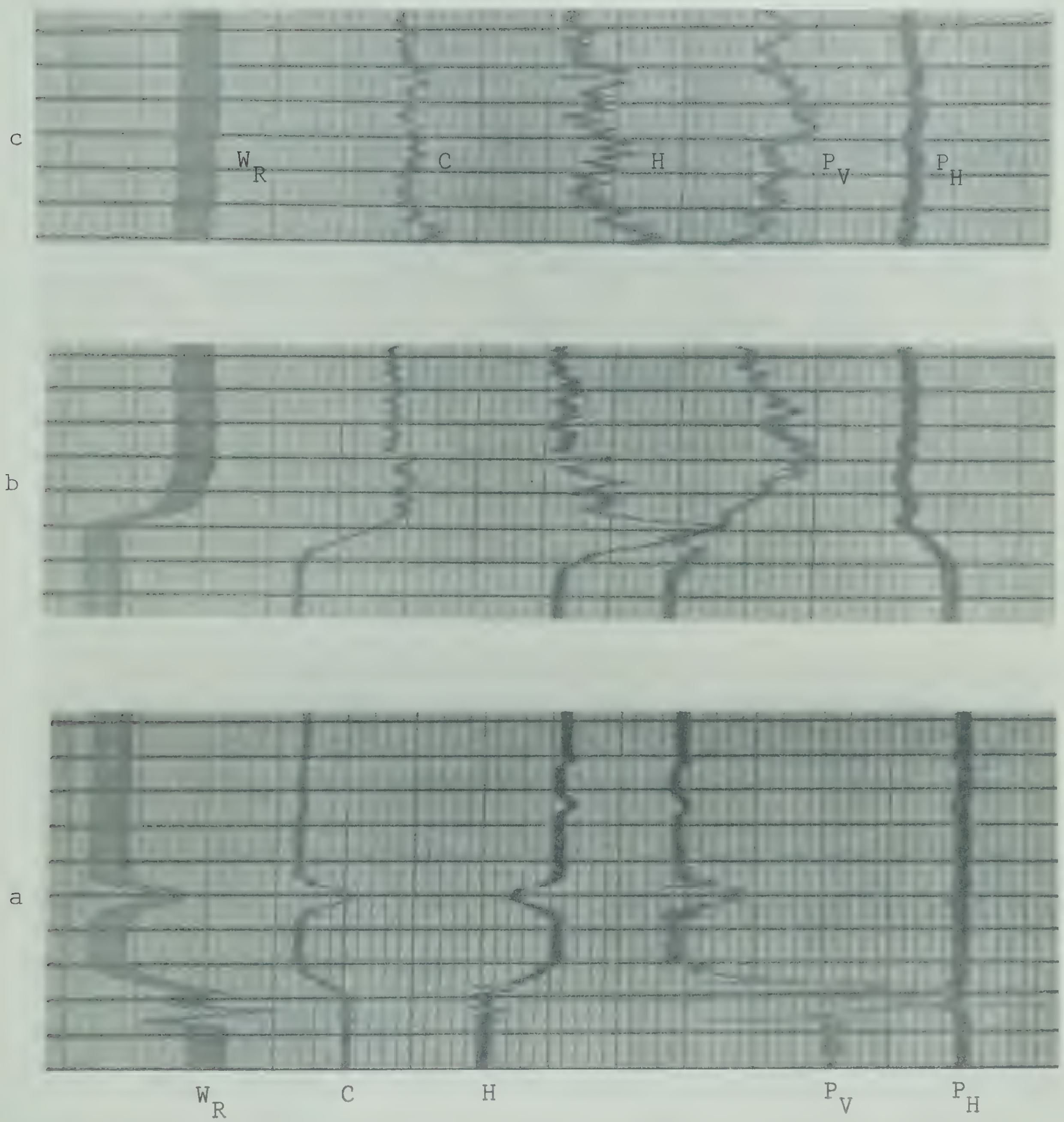


Figure 16 : Typical record chart showing signals from transducers:

(a) cultivator lowered, weight removed from wheels,

(b) penetration of shovels, return of weight to wheels,

(c) signals during the run.

The equations were:

$$A_1 X + B_1 Y = R_1 \ldots\ldots\ldots\ldots (9)$$

$$A_2 X - B_2 Y = R_2 \ldots\ldots\ldots\ldots (10)$$

where (i) R_1 and R_2 are resultant deflections of the two circuits,

(ii) A_1 and A_2 are coefficients of the horizontal component (X),

(iii) B_1 and B_2 are coefficients of the vertical component (Y).

The structure of the equations (No. 9 and 10) totally depended on the calibration curves of the transducer as described in Section 3.3.

5. The magnitude and direction of the vertical and horizontal forces, and the remaining forces were then obtained from their respective calibration curves.

The depth values obtained with the depth measuring device were averaged and the actual speeds of the cultivator were calculated from the run length and recorded times.

4.2. Experimental Error.

All field experiments and measurements involving soil parameters and human factors are inaccurate to some degree, so that the "actual" value or the "accurate" value of a physical quantity cannot be found. However, assuming that an accurate value exists, an estimate of the limits between which this value lies can be obtained.

The error of observation, which is the difference between the observed value of any physical quantity and the accurate value, follows

no simple law and in general arises from many causes. Three categories of error, which have the highest probability to be present in this type of project are:

A. Random errors. These are also called experimental or accidental errors. Presence of these types of errors is due to errors of judgement in instrument readings, fluctuating conditions (such as temperature, line voltage, depth, speed, bulk density), and small disturbances. The small disturbances might be due to hidden stones, short lengths of hard pan in the soil, the shank force transducer hitting localized high bulk density spots, mechanical vibrations of the chassis, and pick-up of spurious signals by the recorder.

B. Systematic errors. This includes personal errors, experimental conditions, imperfect techniques, and errors of calibration of instruments.

C. Illegitimate errors. Errors of computation, blunders, and chaotic errors are included in this category. Most, or even all, of these types of errors are always present, at least to a small degree. However, these errors are avoidable and, hence, were assumed not to be present.

Presence of systematic error in the experiment cannot be denied but there was no way of detecting and subsequently applying a correction to the data. Certainly a study of the histogram of values obtained during the experiment was of no help, since the variations in the readings were due only to random error, and all the readings shared the same systematic error, if at all present.

4.2.1 Estimates of Random Error.

In experimental measurement if q is the correct value of x, then,

$$q = x \pm e \quad \ldots \quad (11)$$

where, e is the likely value of absolute error.

Generally, the error is expressed as in relative or fractional term ε which is equivalent to $\frac{e}{q}$.

A. External estimate of error ε_E. The estimate is based on the knowledge of the experiment, assessment of limitations (such as accuracy in planimetering, accuracy with which a signal can be read on the record chart), and on the knowledge of this type of experimental work carried out by others. Estimated percentage of fractional error was as follows:

(a) Total weight of the cultivator (W) = ± 1%

(b) Horizontal force on the drawbar (P_H) = ± 3%

(c) Vertical force on the drawbar (P_V) = ± 5%

(d) Wheel reaction (W_R) = ± 2.5%

(e) Horizontal force on the shank (L) = ± 5%

(f) Vertical force on the shank (V) = ± 10%

(g) Rolling resistance of wheels (R.R.) = ± 2.5%

(h) Depth of operation (d) = ± 1/2 in.

(i) Speed of operation (s) = ± 2%

(j) Bulk density of the test plot (B.D.) = ± 1.5%

(k) Moisture content (m.c.) = ± 2%.

This estimate included the variation (random error) within a replicate and between replicates.

B. Internal estimate of error ε_I. Repeated measurements do not produce identical values of the quantity being measured, and the variation among the measurement allows an estimate of the accuracy of collected data.

Instantaneous variation in the forces measured on the chassis was quite high and in some cases was more than three times the average value. To obtain an internal estimate of error in the forces measured on the chassis, repeated values at constant speed and depth were made. Effects of moisture content and bulk density were neglected, as the runs considered in this sample analysis were taken within several hours and in the same plot. The range of variation in the moisture content and bulk density was not high enough to invalidate this assumption and affect the sample analysis adversely. Under the circumstances and field setup, replicates at exactly constant speed and depth were not possible. Therefore, to have an on-the-spot estimate of error in forces, the record charts were visually inspected for unexpected variation. The average speed and depth were also used as a check on the force values. Calculated error in the forces are given in Appendix B.

4.2.2 Comparison between internally and externally estimated error.

The difference between the internally and externally estimated error was unsystematic. In most of the cases (out of five cases studied), the internal estimate of random error in the horizontal force on the

hitch, wheel reaction rolling resistance and horizontal force on the shank was either close to or less than the external estimate. A high degree of variation was found to exist in the internal estimate of error in the vertical force on the hitch and shank.

4.3 Force Balance on the Chassis.

The force balance of the instrumented cultivator in the soil having two bulk densities and various moisture contents was studied. To increase the reliability of results concerning the force balance in the horizontal and vertical planes, various combinations of depth, speed, and number of rows of shanks were used.

Equilibrium of forces acting on the chassis were tested by comparing the measured and calculated values of the forces on the shank. These values were obtained for each speed, depth, cutting unit, and number of rows of shanks. Replicates varied from two to five depending on the limitations set by the available plot area.

Simple correlation analysis was carried out on the paired data (measured and calculated) to obtain the correlation coefficient (r). The hypothesis tested was that there was no difference between the measured and calculated values of the forces irrespective of change in speed, depth, cutting unit and the number of rows of shanks. Figures 17 and 18 show the general tendency of the data to approach the zero error line. The correlation coefficients calculated for the horizontal and vertical forces were:

$r_{12} = 0.89$, $n = 80$

$r_{34} = 0.74$, $n = 80$

where,

r_{12} = simple correlation coefficient of the measured and calculated horizontal force,

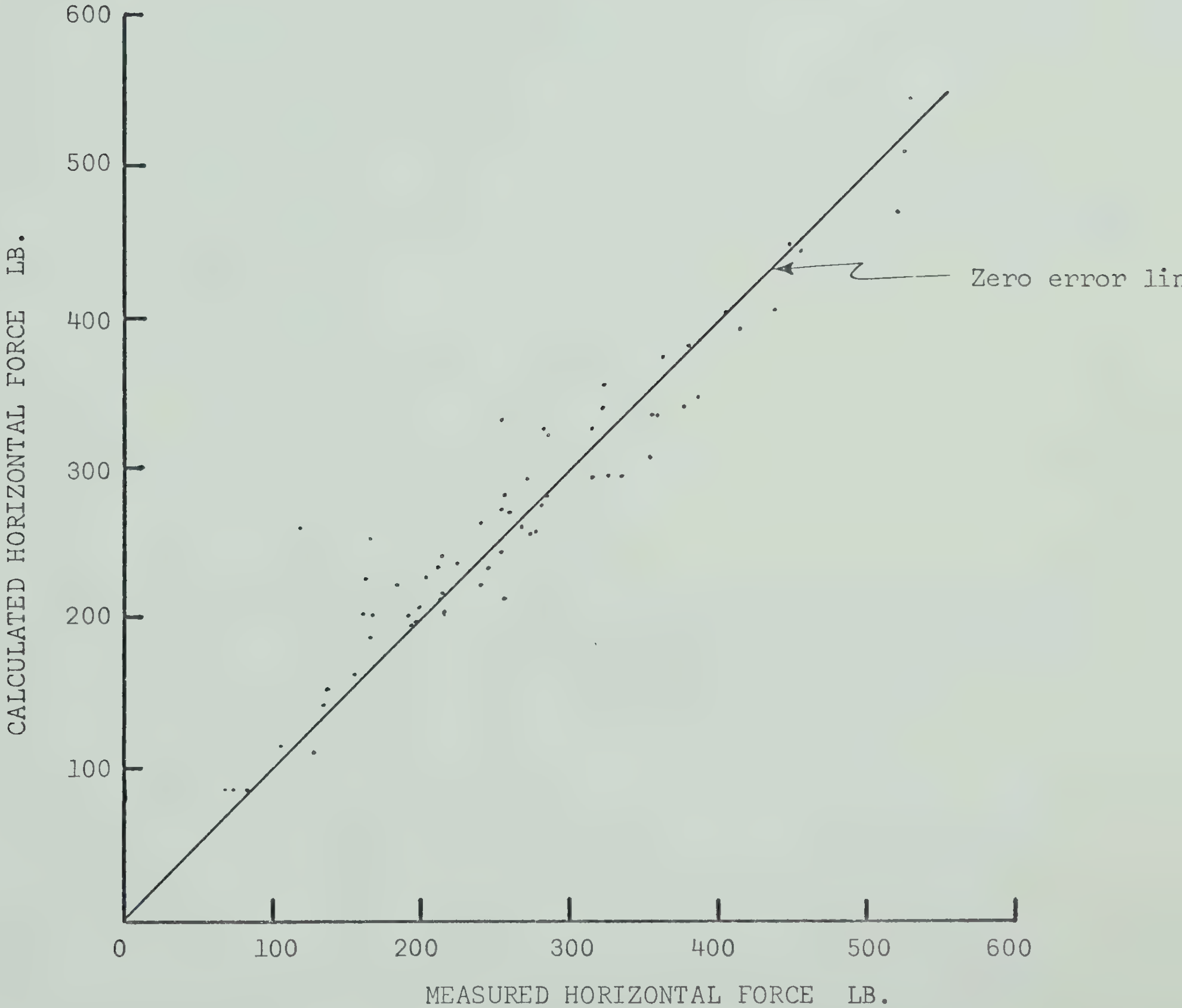


Figure 17: Calculated horizontal force versus measured horizontal force on the shank.

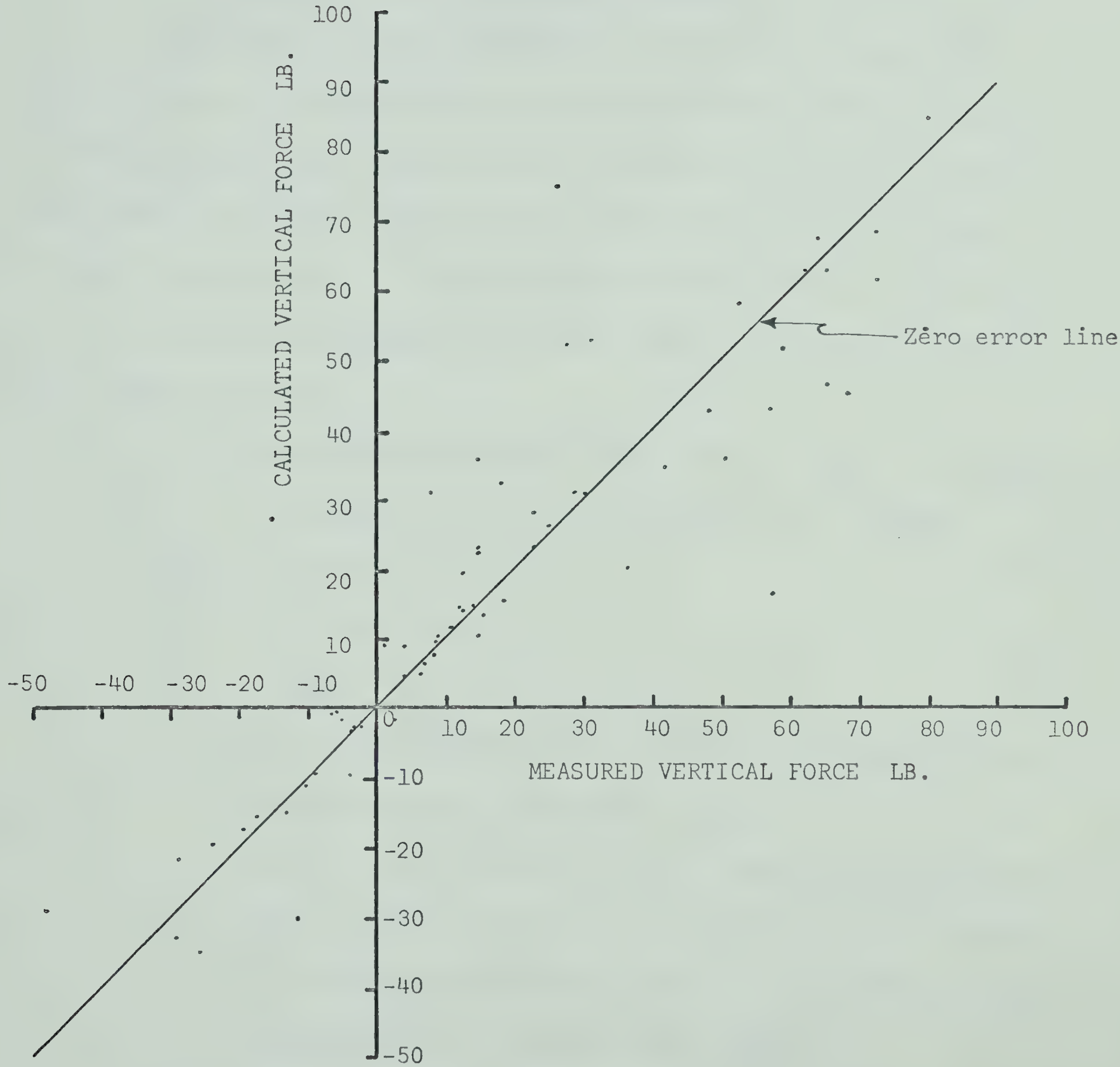


Figure 18: Calculated vertical force versus measured vertical force on the shank.

r_{34} = simple correlation coefficient of the measured and calculated vertical force,

n = number of sets used in the analysis.

Significant positive correlation between the measured and calculated values of the horizontal and vertical forces indicated that the forces acting on the chassis were in equilibrium. The correlation coefficient value of the vertical force balance was smaller than the horizontal force balance. Figure 18 shows scattering of the plotted data which in effect gave a smaller correlation value. This could be due to three possible reasons:

(i) High percentage error in the vertical force on the shank as explained in the first section of this chapter.

(ii) Equations

$$0.893L - 0.83V = H. \quad \text{(A)}$$

$$\text{and} \quad L + V = C. \quad \text{(B)}$$

used for calculating the vertical and horizontal forces on the shank were found very sensitive to the vertical force. A small error in H and C values caused considerable change in the vertical force. These equations correspond to the general equations 9 and 10. The coefficients of the equations were obtained from Figure 4.

(iii) variation between individual shanks and rows.

4.4 Soil Forces Acting on Cultivator Sweeps.

Three forces act on the cultivator in the horizontal plane (a), horizontal component of the resultant soil force (ΣL), (b) rolling resistance of wheels (R.R.), (c) and total draft (P_H). The calculated value of rolling resistance did not vary greatly in similar soil conditions

(Appendix B; Table B-II). Therefore, the governing factors of ΣL would effect P_H to the same degree. Figure 19 shows the effect of depth on the horizontal component of the resultant soil force (L) acting on a shank. The regression lines are the best fit to the data obtained by using a 15½ in. high lift sweep. Prediction of L, from the equations, is limited to the sweeps used in the project, soil conditions (bulk density 1.05 - 1.1, gm/cm^3, moisture content 32 - 38%), and depth (2.5 - 6.5 in.). Presence of error in the data as indicated in section 4.2.1 may limit the extent to which L can be predicted precisely.

Figure 20 shows the effect of speed on L at three depths. Three replicates of each depth were plotted on the same graph to indicate the magnitude of variation that was obtained in the field experiment. At lower depths the effect of speed was less predominant than at higher depths. The dispersion of plotted points was more evident at 4.25 and 6.0 in. depths than at 2.5 in.. Figure 20 also shows that replicates at 4.25 and 6.0 in. depths have low repeatability in comparison to replicates at 2.5 in. depth. All limitations of the depth versus L graph are valid for this graph.

The vertical force (V) on the shank had considerable variation. Figure 21 shows the effect of depth on V. At depths less than 4 in. the direction of V changed from downward to upward. The slopes of the curves were high in the V positive (downward) region and low in the V negative region. A general conclusion drawn from the graph was that an increase in depth increased the downward vertical force on 15½ in. high lift sweeps. In an attempt to evaluate the effect of speed on V, a correlation analysis was performed on the data. At 2 and 4 in. depths the correlation coefficients were not significant, however, at 6 in. depths the correlation between V and speed was high ($r = 0.82$). Figure 22 shows the regression

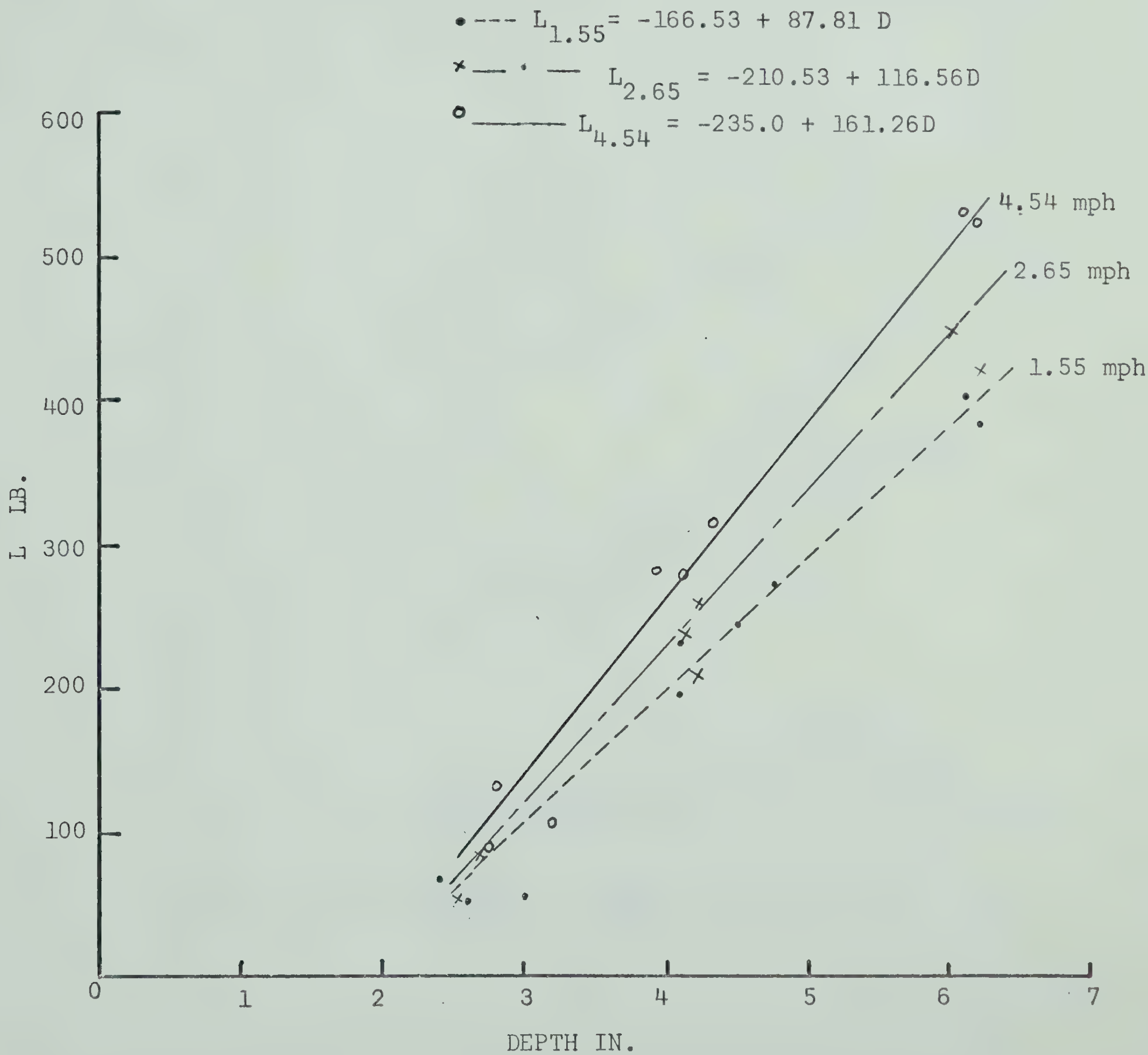


Figure 19: Horizontal force on shank versus depth.

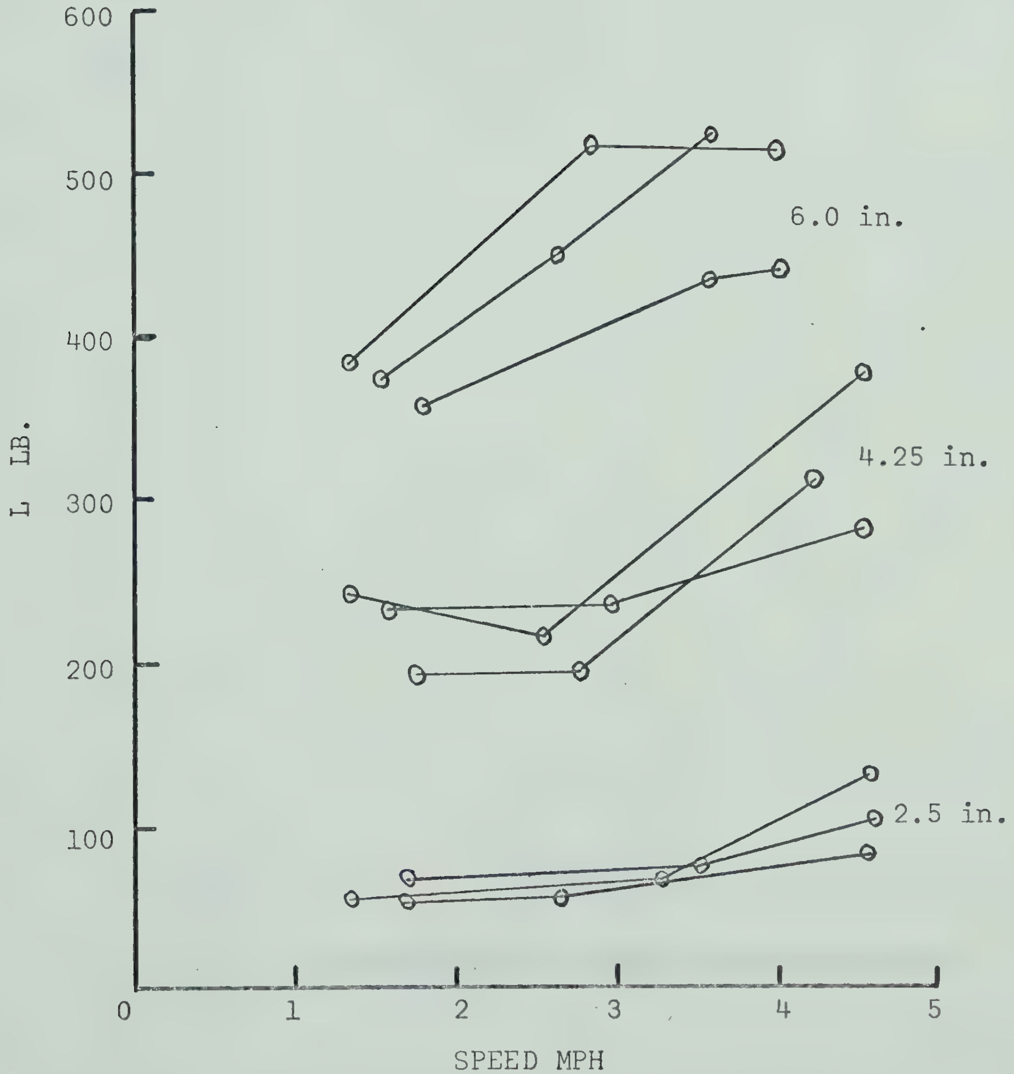


Figure 20: Horizontal force on shank versus speed.

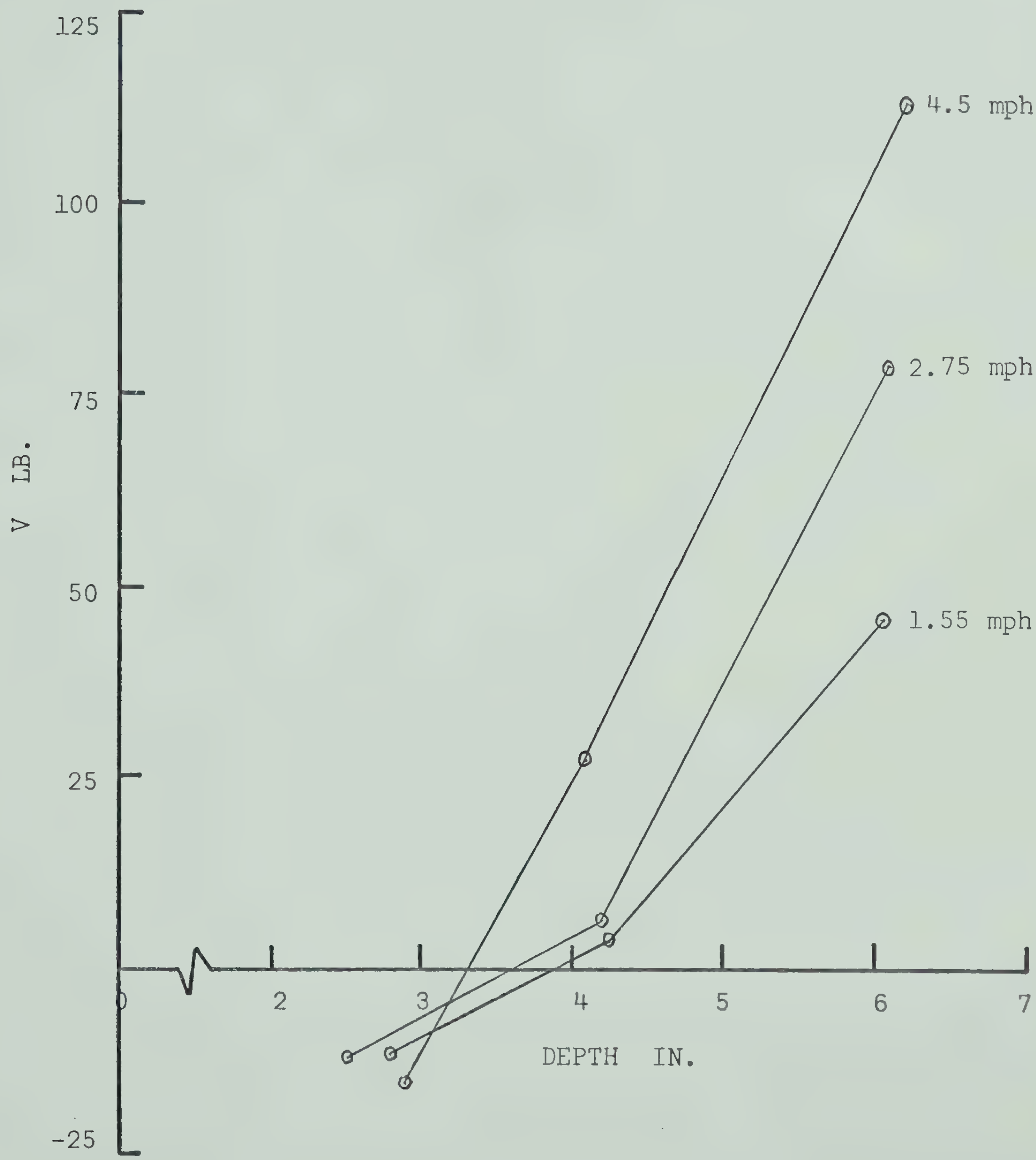


Figure 21: Vertical force on shank versus depth.

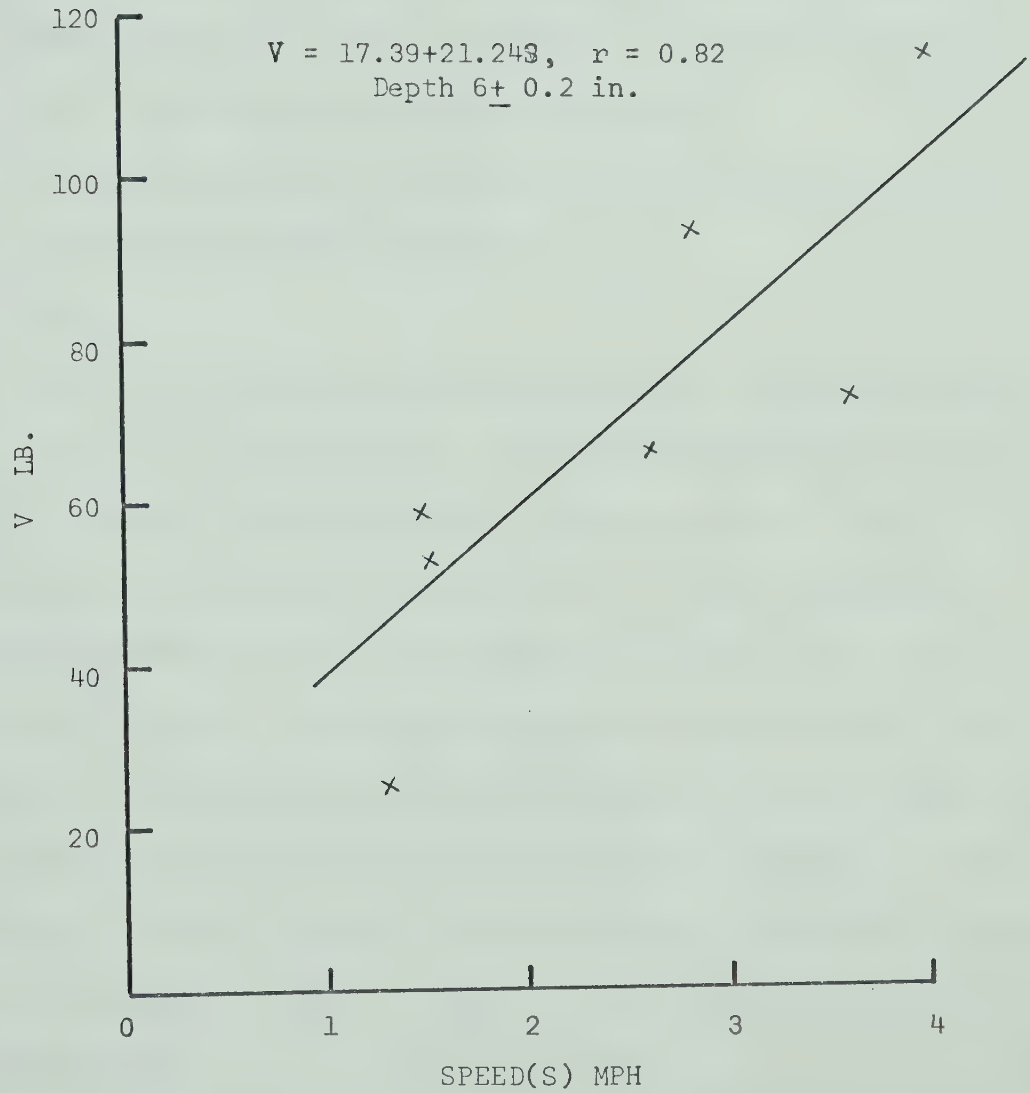


Figure 22: Vertical force on shank versus speed.

line of V on speed at 6 in. depth. Since there was dispersion of the points plotted a possible error existed in the position of the straight line. The standard error of estimate was calculated by using the equation by Thomas (1963) and the value was 14.8 lb.. The high value of the standard error decreased the reliability of the prediction equation (Figure 22). However, a general conclusion that an increase in speed increased the vertical downward force on sweeps remained unaffected.

Limitations mentioned in the beginning of this section were also applicable to the vertical force analysis.

4.5 V/L Ratio.

The study of V/L ratios was undertaken for two important reasons:

1. To obtain V/L ratios and compare with published values,
2. To study the effect of depth and speed on V/L ratio.

The V/L ratios obtained are given in Table 4.1. A simple correlation analysis performed indicated that the correlation between V/L ratio and speed was not significant. The correlation between V/L ratio and depth was very high ($r = 0.98$), however, when the data were plotted (Figure 23) a straight line did not seem to represent the true relationship. The best fit curve for the data was a second degree polynomial (quadratic equation). The equation and curve are shown in Figure 23 which are valid under the following limitations:

(a) data collected by using first two rows of the cultivator and 15½ in. high lift sweep,

(b) speed range 1.5 - 4.5 mph,

(c) operational depth range 2.5 - 6.5 in.,

(d) soil parameters (i) moisture content 32 - 34%

(ii) bulk density 1.05 - 1.10 gm/cm^3.

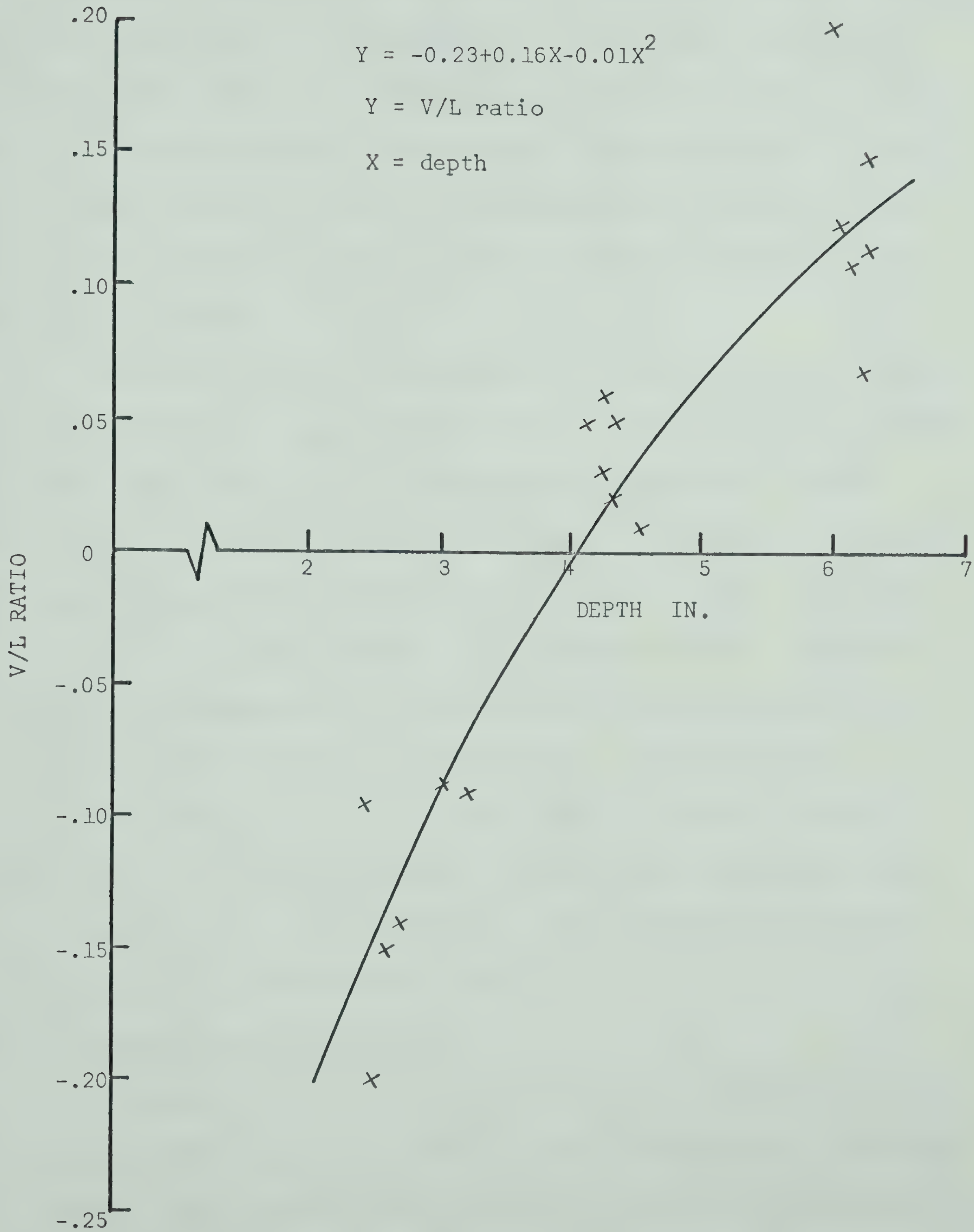


Figure 23: V/L ratio versus depth.

The V/L ratios obtained by using a 16 in. low lift sweep were smaller than obtained by using 15½ high lift sweeps (Table 4.1). In most of the cases V/L values were lower in similar soil conditions. The data was not sufficient to apply a test of significance but the trend could very well be seen from the table. Nichols et al. (1958) found that a change in sweep angle changes V/L ratio. This supported the different values of V/L ratios obtained by using two types of sweeps of different lift angles in this project.

Conversely, the V/L ratios obtained by using 2 in. chisel points (for 4 in depths) were larger than for 15½ in. high lift sweeps in similar soil conditions. Also, the data collected in compacted soil (bulk density 1.16 - 1.17 gm/cm^3) using 15½ in. high lift sweeps and 2 in. chisel points gave larger V/L values than those obtained in normal soil (bulk density 1.05 - 1.10 gm/cm^3) (Table 4.1). The data were not sufficient to arrive at definite results and required more replicates to establish a relationship among V/L ratios, cutting units, and bulk density.

The V/L ratio obtained by Sirohi (1967) in chapter 2, page 19 was very high (.4 to .5) when compared with the values obtained in this project. However, the sweeps used in the investigation were different and the tests were performed in soil bins.

4.6 Vertical Force on the Hitch.

The study of P_V and the factors governing its magnitude was one of the primary objectives of the project. Two important areas influenced by P_V are (a) weight transfer from implement to tractor and (b) design of drawbar and hitch. The following factors affecting the vertical force on the hitch were given by Clyde (1970):

Table 4.1: V/L ratio.

Date	V/L ratio	Depth (in.)	Speed mph
	Normal soil (bulk density 1.05 - 1.1 gm/cm^3)		
10/9/70*	0.05	4.3	1.54
10/9/70*	0.03	4.2	3.09
10/9/70*	0.02	4.3	4.53
25/8/70*	0.05	4.1	1.75
25/8/70*	0.06	4.2	2.73
25/8/70*	0.10	4.3	4.26
25/8/70*	0.20	5.9	1.52
25/8/70	0.15	6.0	2.62
25/8/70*	0.14	6.1	3.59
19/8/70*	0.17	6.2	1.30
19/8/70*	0.11	6.1	2.83
19/8/70*	0.15	6.2	3.98
25/8/70*	-0.15	2.6	1.71
25/8/70*	-0.20	2.5	2.62
25/8/70*	-0.14	2.7	4.55
19/8/70*	-0.10	2.4	1.70
19/8/70*	-0.09	3.0	3.49
19/8/70*	-0.09	3.2	4.59
18/8/70*	0.01	4.5	1.31
18/8/70*	0.02	4.2	2.52
18/8/70*	0.06	3.9	4.53
17/8/70*	-0.01	4.1	1.58
17/8/70*	-0.01	4.1	2.96
17/8/70*	-0.03	4.1	4.53
27/8/70**	0.06	4.4	1.71
27/8/70**	0.03	5.3	3.41
27/8/70**	0.01	4.8	4.01
26/8/70**	0.00	4.0	3.25
26/8/70**	0.00	4.0	4.01
26/8/70**	-0.17	4.0	1.63
26/8/70**	-0.17	4.0	3.93
26/8/70**	-0.12	3.9	4.55
27/8/70**	0.08	6.6	1.70
27/8/70**	-0.05	6.2	3.59
27/8/70**	0.16	6.2	4.01
26/8/70**	0.16	5.8	1.77
26/8/70**	0.08	5.9	3.59
26/8/70**	0.04	5.6	4.08
9/9/70***	0.29	4.6	1.54
9/9/70***	0.13	4.5	3.40
9/9/70***	0.12	4.4	4.86

Cont'd.

Table 4.1: Continued.

Date	V/L ratio	Depth (in.)	Speed mph
9/9/70***	0.10	4.8	1.62
9/9/70***	0.16	4.4	3.24
9/9/70***	0.11	4.4	4.86
	Compacted soil (bulk density 1.16 - 1.17 gm/cm^3)		
10/9/70***	0.22	4.4	1.54
10/9/70***	0.29	4.1	3.09
20/8/70*	0.14	4.3	1.66
20/8/70*	0.16	4.2	3.09
20/8/70*	0.18	4.5	1.66
20/8/70*	0.16	4.1	3.24

Note: * 15½ in. high lift sweep.
** 16 in. low lift sweep
*** 2 in. chisel point.

First and second rows of cultivator were used to obtain the data.

1. Height and longitudinal position of hitch point.
2. Magnitude of ΣL.
3. Location and magnitude of ΣV.
4. Position and magnitude of W and W_R.
5. Rolling resistance of wheels.

For a balanced cultivator the wheels tend to act as a pivot. Therefore, to establish a functional relationship between P_V and ΣL, ΣV, W, and R.R. moments were taken about the intersection of the line of action of W_R and P_H. From the known geometry of the cultivator, drawbar height (15 in.) and for a given depth of operation (4 in.), the moment equation was

$$P_V = 0.142\ \Sigma L - 0.185\ \Sigma V - W(0.01 - 0.12\ \rho) \quad \ldots\ldots\ 11$$

where ρ = coefficient of rolling resistance.

The coefficient of rolling resistance in two soil conditions was 0.134 and 0.054 respectively. For a given total weight of cultivator (2324.5 lb), the contribution due to W was only 9.3 lb.. The coefficient of W in equation 11 did not change significantly in the 2 - 6 in. depth range. Therefore, the effect of W on P_V was regarded as constant for the same total weight of the cultivator and soil conditions. Also, the direction of ΣV changed (upward) in 1.5 - 4.5 in. depth range leading to the change in sign of the term containing ΣV in equation 11.

To test the extent to which ΣL and ΣV determine P_V, a multiple correlation analysis was performed on 11 sets of data shown in Table 4.2. The coefficients of determination (r^2) obtained from the analysis were

$$r^2_{P_V \cdot \Sigma V\ \Sigma L} = 70\%$$

$$r^2_{\Sigma V . \Sigma L\ P_V} = 36\%$$

$$r^2_{\Sigma L . \Sigma V\ P_V} = 73\%$$

This analysis indicated that 70% of the variation in P_V is due to the combined effect of ΣV and ΣL. The data although not free from random error still provided sufficient grounds for the validity of equation 11 .

Table 4.2 . Forces used in the multiple correlation analysis (three variables).

P_V lb.	ΣV lb.	ΣL lb.	Depth in.	Speed mph
186.9	-694.2	2028.0	1.9	1.20
163.8	-427.7	2811.9	2.9	0.90
157.2	-856.7	2104.7	2.1	2.73
174.9	-390.0	2272.4	2.7	4.10
155.4	189.0	2828.0	3.9	1.57
173.2	380.8	2626.0	4.0	1.54
218.4	200.2	2467.4	3.9	1.48
247.8	123.6	4561.0	4.3	1.34
274.2	19.5	3292.5	5.9	1.10
300.6	189.8	4966.0	6.0	2.04
301.9	257.4	5239.0	6.0	2.72

Note: The data were collected using 15½ in. sweeps and three rows of the cultivator.

Soil parameters: Bulk Density 1.01 - 1.05 gm/cm^3.

Moisture Content 39 - 47%.

Weight transfer from implement to tractor.

Coleman (1969) suggested that the dominant term $P\frac{h_1}{d_1}$ (chapter 2) is the largest contributor to the magnitude of P_V. Therefore to compare the value of the dominant term ($P\frac{h_1}{d_1}$) with the measured P_V, the magnitude of P_V was corrected for initial conditions. The measured value of P_V included the static weight acting on the hitch (P_{Vst}). Therefore, $P_V - P_{Vst} = P_{Vabs}$ can be compared to the value calculated from Coleman's dominant

term.

From the known values of the parameters, P_{Vabs} and $P\frac{h_1}{d_1}$ were calculated and some examples are given in table 4.3.. Table 4.3 indicates that the force obtained from the term suggested by Coleman does not compare with P_{Vabs}. The analysis of error had indicated high fractional random error in P_V (section 4.2.1) in some cases. But even after applying the correction, the value of P_{Vabs} were considerably less than $P\frac{h_1}{d_1}$ at 4 and 6 in. depths.

Table 4.3. Comparison between P_{Vabs} and dominant term.

P_{Vabs} lb.	$P\frac{h_1}{d_1}$ lb.	Depth in.	Speed mph	Moisture Content %
202.3	343.9	2.9	0.90	49.1
195.7	249.3	2.1	2.73	49.1
213.4	307.8	2.7	4.10	49.1
193.9	408.5	4.3	1.57	40.0
211.7	408.2	4.2	1.54	40.0
256.9	380.3	4.0	1.48	40.0
232.5	737.3	5.9	0.96	35.8
235.2	696.5	6.1	2.41	35.8
243.0	714.6	6.1	3.42	35.8

Note: The data were obtained by using 15½ in. high lift sweeps and three rows of the cultivator. The average bulk density of the plot was 1.075 gm/cm^3.

The forces (W_R, R.R.) neglected by Coleman in the calculation of the vertical force on the drawbar did not significantly affect the value of the dominant term. Therefore, when these two types of correction failed to explain the wide difference between calculated and measured vertical force on the drawbar, it was hypothesized that the difference might be due to the following:

A. "Tractor effect" on the force transducer. Table 4.3 indicated that from 4 to 6 in. depth a proportionate increase in $P\frac{h_1}{d_1}$ is much greater than from 2 to 4 in. depth. Also, in the dominant term h_1 and d_1 did not change very much as depth changed. Therefore, high values of $P\frac{h_1}{d_1}$ were only due to an increase in P. On the contrary, the proportionate change in P_{Vabs} was small and the difference between P_{Vabs} at 6 in. depth and P_{Vabs} at 2 in. depth was not great. Hence the large difference between measured and calculated vertical force may have been due to a "tractor effect" on the measured vertical force on the drawbar. A "tractor effect" on the measurement of P_V was possible if the tractor drawbar was not horizontal in operation. In this condition the line of action of P_H and ΣL + R.R. would not coincide which in effect would cause a bending moment opposite in direction of P_V. This would result in a lower magnitude of measured P_V than the actual.

An increase in the drawbar pull results in an increase in weight transfer from the front wheels to the rear wheels of the tractor. At 6 in. depth of operation, the P_H value was as high as 5000 lb. At this value of P_H, the weight

transfer from front wheels to rear wheels of the tractor would be approximately 1000 lb. and the rear tires would deflect and sink in the ground by 0.25 in. (found in laboratory tests).

Another possibility of the tractor drawbar not being horizontal in operation would be due to the digging effect of the rear tires. McLeod et al. (1963) have given some information about the volume of soil displaced by a 13.6 - 38, 6 ply single tire at 12 and 18 psi inflation pressures. The data indicated that the depth of digging at maximum permissible load may be as high as 3.5 in. in Lloyd clay (bulk density 0.96 gm/cm^3, moisture content 21.6%).

A combination of these effects (tire sinkage plus tire deflection) could seriously effect the assumption that the drawbar remained horizontal. Also, assuming that the theoretica values of P_V calculated by moments are correct, some slack in the fitting of the transducer on the drawbar would add further to the tractor effect. Some values of P_V (measured) and their corresponding values calculated by (a) moments about the intersection of W_R and R.R. and (b) by considering the effects mentioned above are given in Appendix B. The data substantiates the assumption that the vertical force sensed by the transducer was not the actual vertical force applied by the cultivator.

B. Presence of large systematic error in the data is also one of the possibilities. However, the presence of 300% error (at 6 in. depth) seems rather impossible and inconceivable.

An example of extreme variations in the measured values of P_V.

Figure 24 is typical of the wide variation in measured value of P_V. Very large fluctuations in P_V usually occurred during large changes ($\pm$ 20%) in P_H. Noticeable changes also occurred in W_R. Table 4.4 gives a second by second time line analysis of the measured forces.

In Figure 24 it can be seen that P_V had a rapid increase while P_H was decreasing (time lines 12 - 14) and the highest value of 608 lb. was obtained during a decrease in P_H. This is contrary to theory and further suggests that an external force (from the tractor) was influencing the vertical force on the hitch. Additional rapid increases and decreases (time lines 14 - 17 and 17 - 20) cannot be explained by a change in P_H. Note that the value of P_V changed from 608 to 101 lb. in two seconds while P_H decreased by 600 lb. and W_R increased by 320 lb.

If the vertical forces W_R, P_V and W are used to calculate ΣV, it becomes evident that (barring extreme variations in the actual ΣV) there was an external vertical force on the drawbar changing P_V and W_R. The calculated value of ΣV varies from +91.5 @ time line 15 to +277/5 @ time line 20. These variations are considered too extreme to be due to soil variability alone.

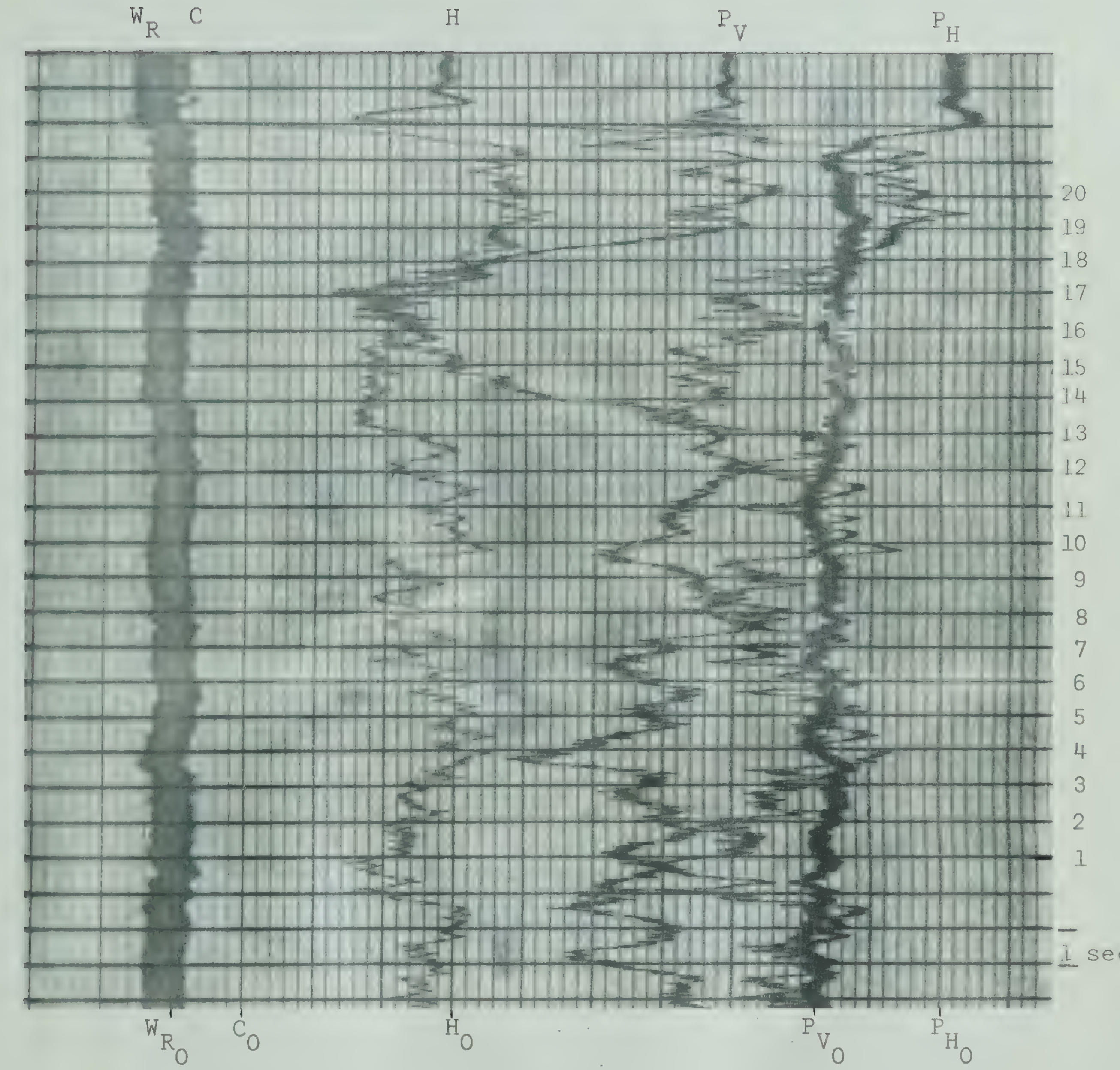


Figure 24: Record chart showing extreme variations in signals.

Table 4.4: Second by second time line analysis of forces (Figure 24).

Second Line	W_R (lb.)	P_H (lb.)	P_V (lb.)	L (lb.)	V (lb.)	R.R. (lb.)
20	2208.0	4230.0	54.0	473.9	19.8	295.9
19	2328.0	3820.0	101.0	447.1	2.2	311.9
18	2148.0	4116.0	454.5	428.0	-6.0	287.8
17	1908.0	4410.0	608.0	268.2	-43.9	255.7
16	1908.0	4939.2	544.0	302.8	-27.1	255.7
15	1908.0	4233.6	498.0	237.8	-29.3	255.7
14	1888.0	4116.0	299.0	241.9	-41.0	253.0
13	2248.0	4351.2	75.5	345.6	-48.3	301.2
12	2288.0	4851.0	49.5	288.2	-28.6	301.2
11	2448.0	5409.6	133.5	341.6	-36.6	301.2
10	2168.0	5145.0	202.5	382.0	-7.3	290.5
9	2208.0	4704.0	106.0	307.6	-11.7	295.9
8	2248.0	4793.2	94.6	307.6	-11.7	301.2
7	2248.0	5056.8	159.2	295.5	-5.9	301.2
6	2308.0	4704.0	183.8	382.0	-7.3	309.3
5	2248.0	4998.1	182.0	282.0	-7.3	301.2
4	2048.0	5233.2	323.7	405.3	-38.1	274.4
3	2248.0	4351.2	186.5	328.9	-36.6	301.2
2	2248.0	4468.8	141.2	280.8	-7.3	301.2
1	2248.0	4792.0	227.7	261.3	-24.2	301.2

Note: The data were collected on July 15, 1970 at 4 in. depth and 3 m.p.h. speed using 15½ in. high lift sweep and 3 rows of cultivator.

4.7 Wheel Reaction

Figure 16 shows the response of the wheel during a test run. The wheels carried the weight of the cultivator when the shovels were not touching the ground surface. At the start of the run, (a) the cultivator was lowered and the weight carried by the wheels was slowly transferred to the shovels, (b) the suction force and the static weight of the cultivator caused the shovels to penetrate the soil surface to the depth allowed by the hydraulic ram setting. In the process of penetration which lasted one to two seconds depending on the speed and depth of the run, the wheels regained weight necessary to balance the vertical forces on the chassis.

The magnitude and direction of the wheel reaction were calculated from the diagram shown in Figure 25. Moments were taken about point A and the resulting equation was

$$\Sigma M_A = \frac{\rho W_R}{2} \times c + F_x a - \frac{W_R}{2} \times b = 0 \quad \text{(12)}$$

where ρ = coefficient of rolling resistance,

W_R = wheel reaction,

F = vertical force sensed by the wheel reaction transducer.

With known values of a, b and c, the equation reduced to:

$$W_R = F \quad \text{(13)}$$

The signal coming from the wheel reaction transducer was found to be the least sensitive (with less variation) than the other signals. This might have been due to three principal reasons:

(i) less sensitive to change,

(ii) wheel ground contact acting as a momentary shock absorber,

(iii) combined effect of other forces.

Four forces were acting on the chassis in the vertical plane:

1. Total weight of cultivator (W),
2. wheel reaction (W_R),
3. vertical force on the hitch (P_V),
4. vertical force on the shanks (ΣV).

The total weight was constant for any particular run and the remaining three varied according to depth, speed, draft, and soil variables. The direction of the wheel reaction and vertical force on the hitch was upward while the vertical force on the shank changed in direction from upward to downward depending on the run. Analysing the effect of wheel reaction on the remaining two forces (P_V and V), three major cases were considered:

I $W_R > W$

II $W_R < W$

III $W_R = W$.

For Case I, ΣV must be greater than P_V and act downward; for Case II, ΣV may act either upward or downward but the magnitude of ΣV must not be greater than P_V when acting upward; for Case III, ΣV must be equal to P_V and act downward. Examples of three cases are given in Table 4.5.

Table 4.5: Effect of P_V and ΣV on wheel reaction.

	W_R (lb.)	W (lb.)	ΣV (lb.)	P_V (lb.)
Case I	2266	2040.25	427.2	241.9
	2090	2040.25	246.0	200.7
	2226	2040.25	392.0	212.2
Case II	1906	2040.25	-60.4	88.8
	1926	2040.25	-17.6	104.8
	1946	2040.25	101.0	208.7
	1966	2040.25	88.0	170.1
Case III	2026	2040.25	205.0	225.0

Examples of the three cases indicated fairly close agreement between the expected and measured values of W_R, ΣV and P_V to keep the chassis balanced. The fractional random error in ΣV and P_V was quite high (section 4.2.1). This could be explained by looking at the data of Table 4.5 . As expected, the magnitude of ΣV and P_V is small in comparison with W_R. One percent variation in W_R would require as high as one hundred percent variation in ΣV and twenty five percent variation in P_V if one of the two is assumed constant in turn. Normally the situation would be different and P_V and ΣV would vary simultaneously. Therefore, the net variation requirement of ΣV and P_V would be either less than or more than the above-mentioned values. These requirements must be fulfilled to maintain the equilibrium of forces in the vertical plane.

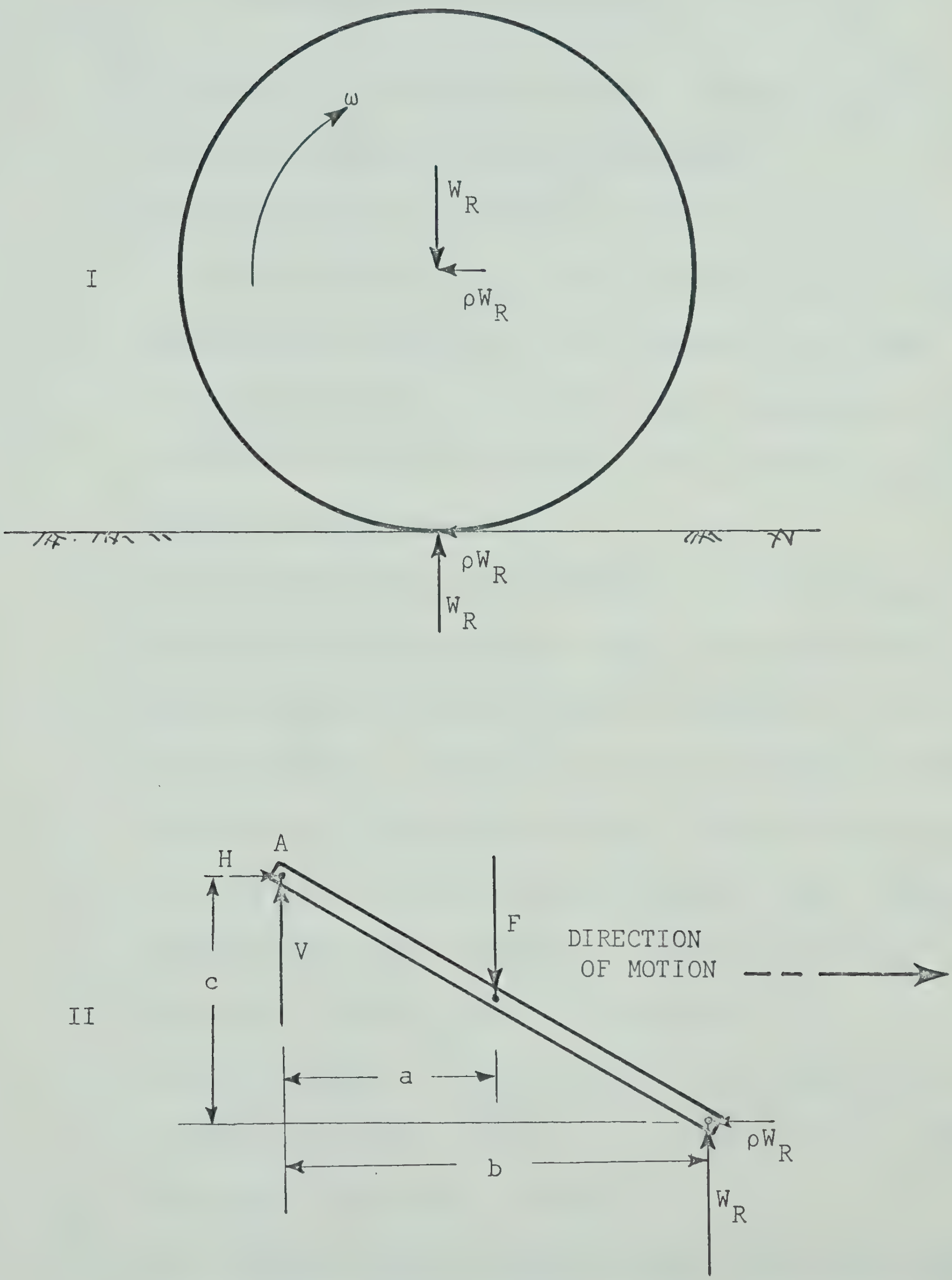


Figure 25: Force analysis of wheel reaction transducer.

Chapter 5

OBSERVATIONS AND CONCLUSIONS

1. The study of a cultivator chassis mechanics is a complex subject due to soil variability.
2. Forces measured on the chassis varied considerably in the same type of soil. An increase in depth or speed increased the deviation of the measured forces from their mean values. In extreme cases, the vertical force acting on the hitch and cutting units varied more than three times the average.
3. The correlation analysis performed to test the equilibrium of the forces acting on the chassis indicated that in approximately 75% of the cases the horizontal forces were in equilibrium. However, in only 55% of the cases were the vertical forces in equilibrium. This was mainly due to a large percentage error in vertical forces acting on cutting units and disagreement between measured and calculated vertical force on the hitch.
4. A moment balance of the forces on the chassis could not be obtained in most of the cases. More accurate values of all the forces were required.
5. An increase in speed or depth increased the horizontal component of the resultant soil force. However, an increase in depth had far greater effect than an increase in speed. Also at shallow depths the effect of speed on the horizontal component of soil force was less pronounced

6. The vertical component of the resultant soil force varied directly with depth. The data was limited to 2, 4 and 6 in. depths which did not permit the evaluation of the true relationship between depth and vertical force on the cutting unit. However, the proportionate increase in vertical force was more at higher depths and speeds. The correlation between speed and vertical force was significant only at the 6 in. depth.

7. The correlation between V/L ratio and speed was not significant. The effect of depth on V/L ratio was highly significant and a second degree polynomial (quadratic equation) was used to represent the relationship.

8. A small increase in the total draft generally resulted in a decrease in wheel reaction and an increase in vertical force on the hitch. However, a much larger increase in the draft had just the opposite effect on the wheel reaction and vertical force on the hitch. A large increase in draft requirement resulted in increased tractor wheel slip and wheel sinkage. Also, the vertical force on the cutting units increased (downward) causing an increase in the wheel reaction and together with the extra wheel sinkage, decreased the vertical force on the hitch.

9. The measured vertical force on the hitch was the net effect, that is, this included vertical force due to the cultivator (downward) and vertical force (upward) due to the angle of

drawbar and hitch. These two forces increased in magnitude as draft increased which resulted in a small increase in the measured vertical force at higher depths. From the standpoint of weight transfer from cultivator to tractor, this phenomenon revealed that the extra weight on the rear wheels of a tractor is not obtained when it is needed.

Chapter 6

RECOMMENDATIONS FOR FURTHER WORK

Based on the results obtained in this study the following suggestions were made for further work:

1. The test plot should be statistically designed to separate the interaction effect present due to uncontrolled parameters.
2. The test plot selected should be fairly level, uniform, and representative of the area.
3. At least one strain gauged shank should be used in each row of a multi-row cultivator to minimize the chance of obtaining non-representative values of vertical force (V) acting on cutting units.
4. Dynamic wheel reaction (W_R) should be measured on both wheels of this type of cultivator to obtain an average value for data analysis. This arrangement would provide a check on the wheel reaction and a comparative measure to detect an erroneous W_R value given by any one of the two wheels.
5. The transducer sensing vertical and horizontal forces on the hitch should be corrected for non-horizontality in operation. This would take care of non-horizontality produced by weight transfer from front wheels to rear wheels of the tractor, weight transfer from the implement to the tractor, digging effect of rear wheels of the tractor, and some slack in transducer-drawbar connection.
6. Speed and depth should be recorded on the go to obtain a better average of the depth and speed. A simultaneous recording of distance would be helpful in visualizing the

magnitude of acceleration and deceleration because of the variation in speed. This would give an idea about the inertia effect on the forces.

7. Preliminary test runs should be analysed and a complete checking of the forces should be made by force and moment balances before full scale testing.

8. More data should be collected by using 16 in. low lift sweeps and 2 in. chisel points (commonly used by farmers) in soils of different types and bulk densities.

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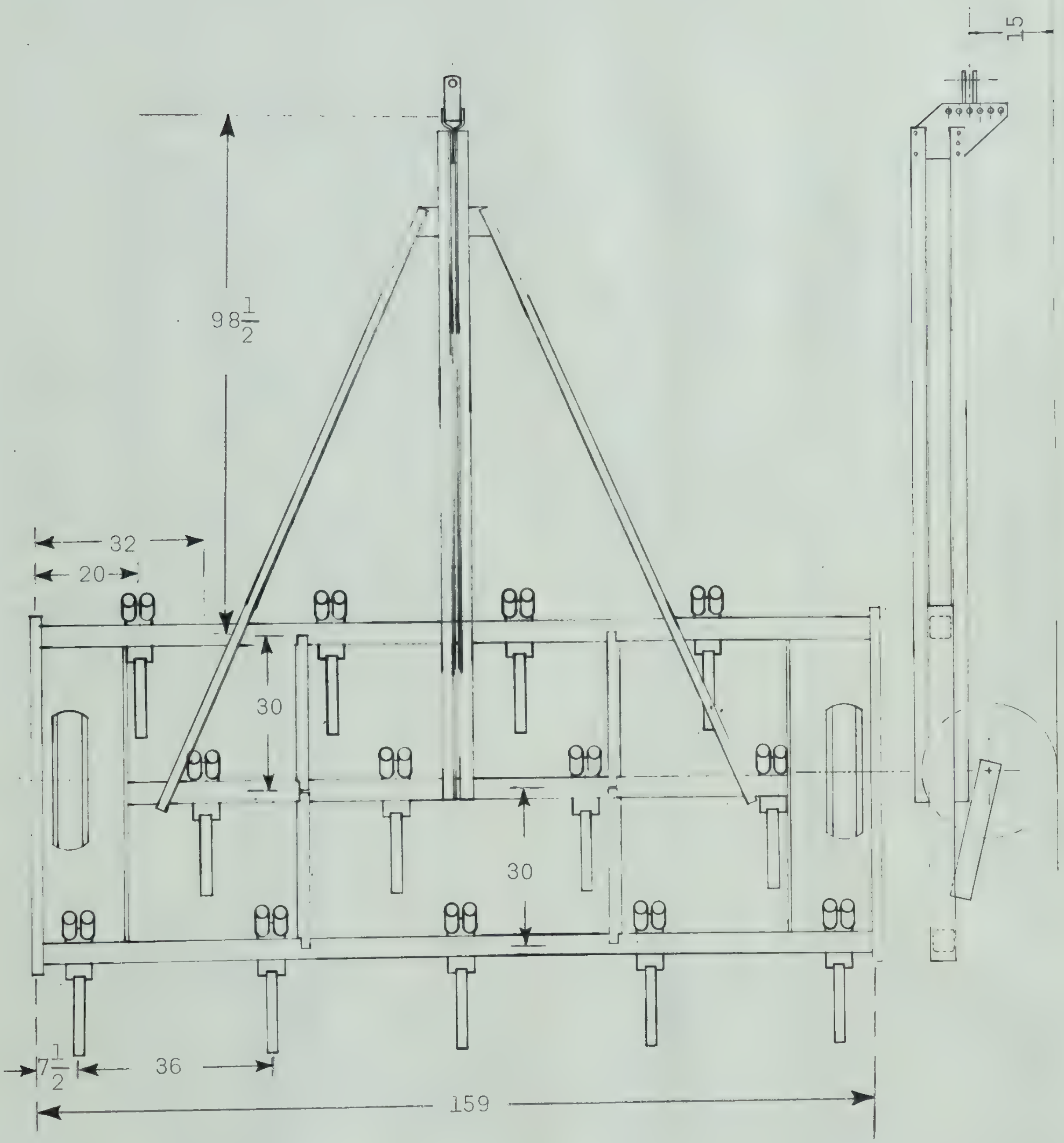
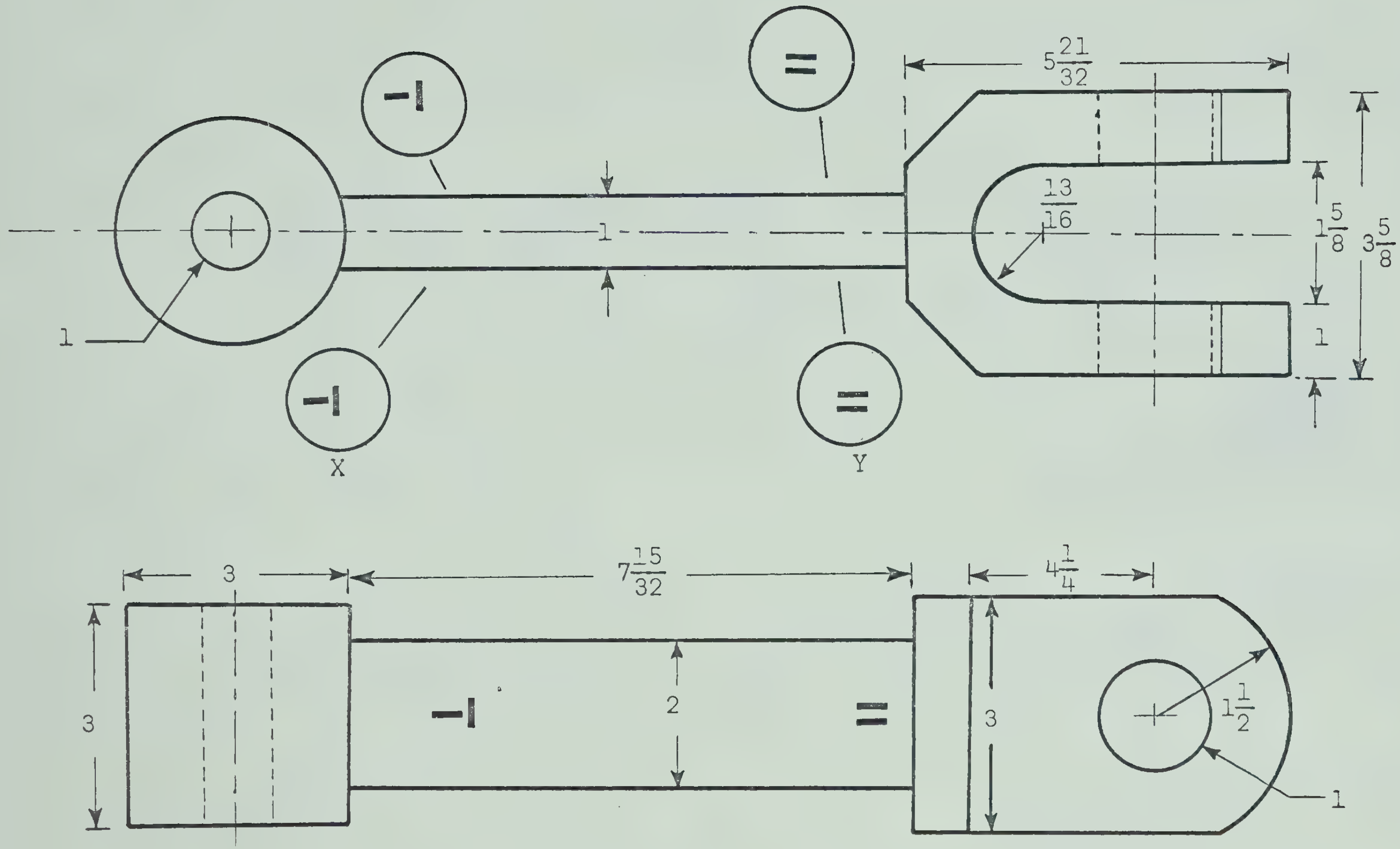
APPENDIX A



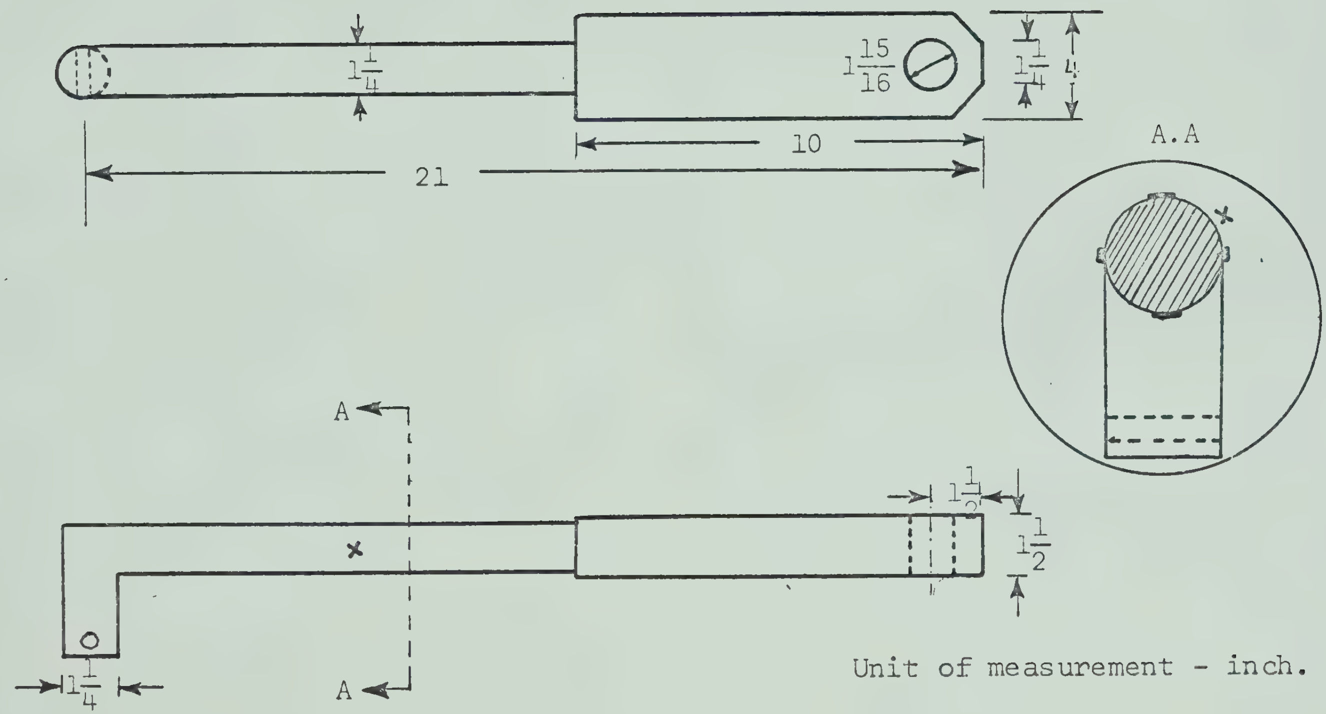
Unit of measurement - inch.

A-I: Cultivator chassis.



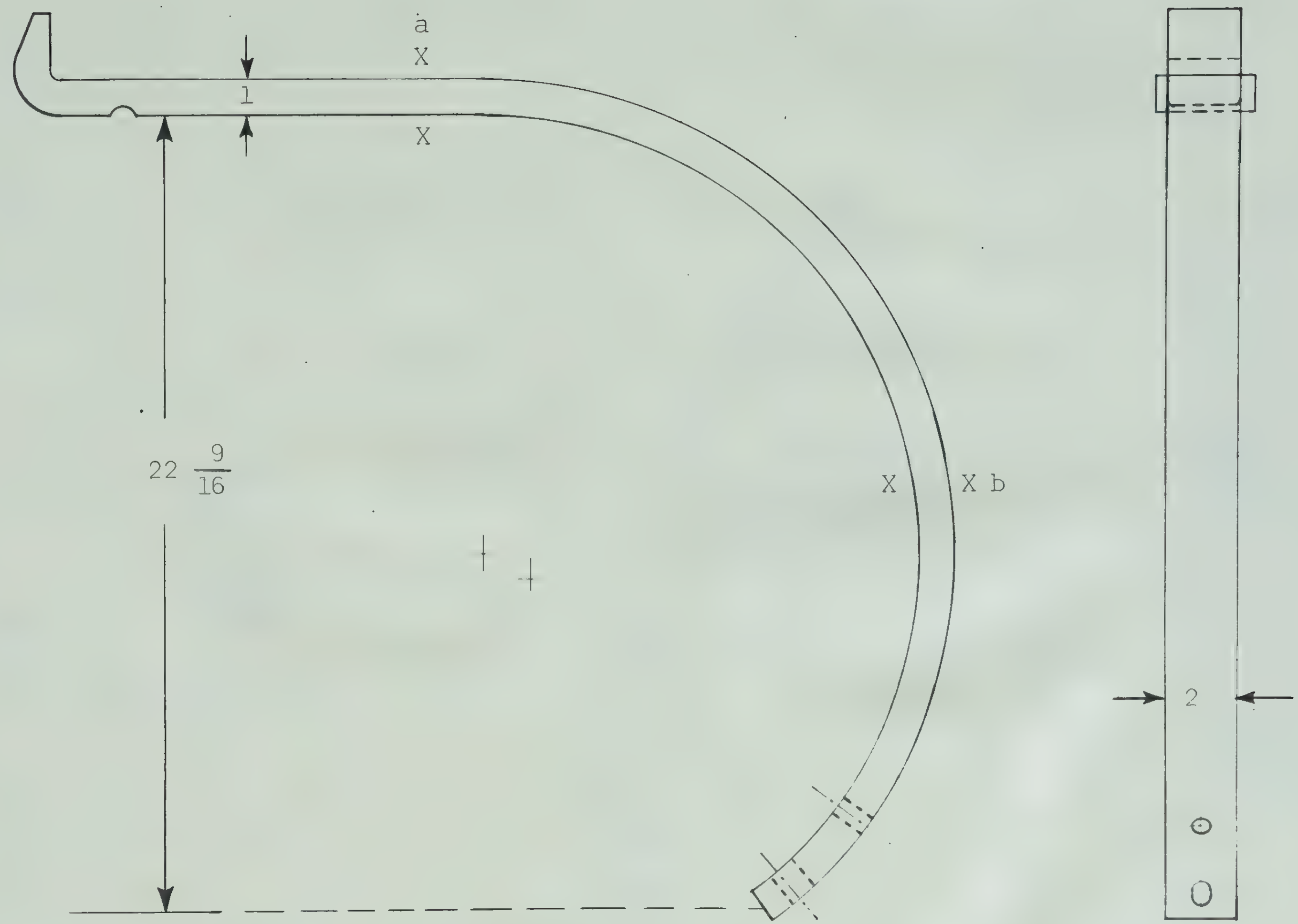
Unit of measurement - inch.

A-II: Dimensions of hitch link transducer (including arrangement of gauges to sense vertical (Y) and horizontal (X) forces).



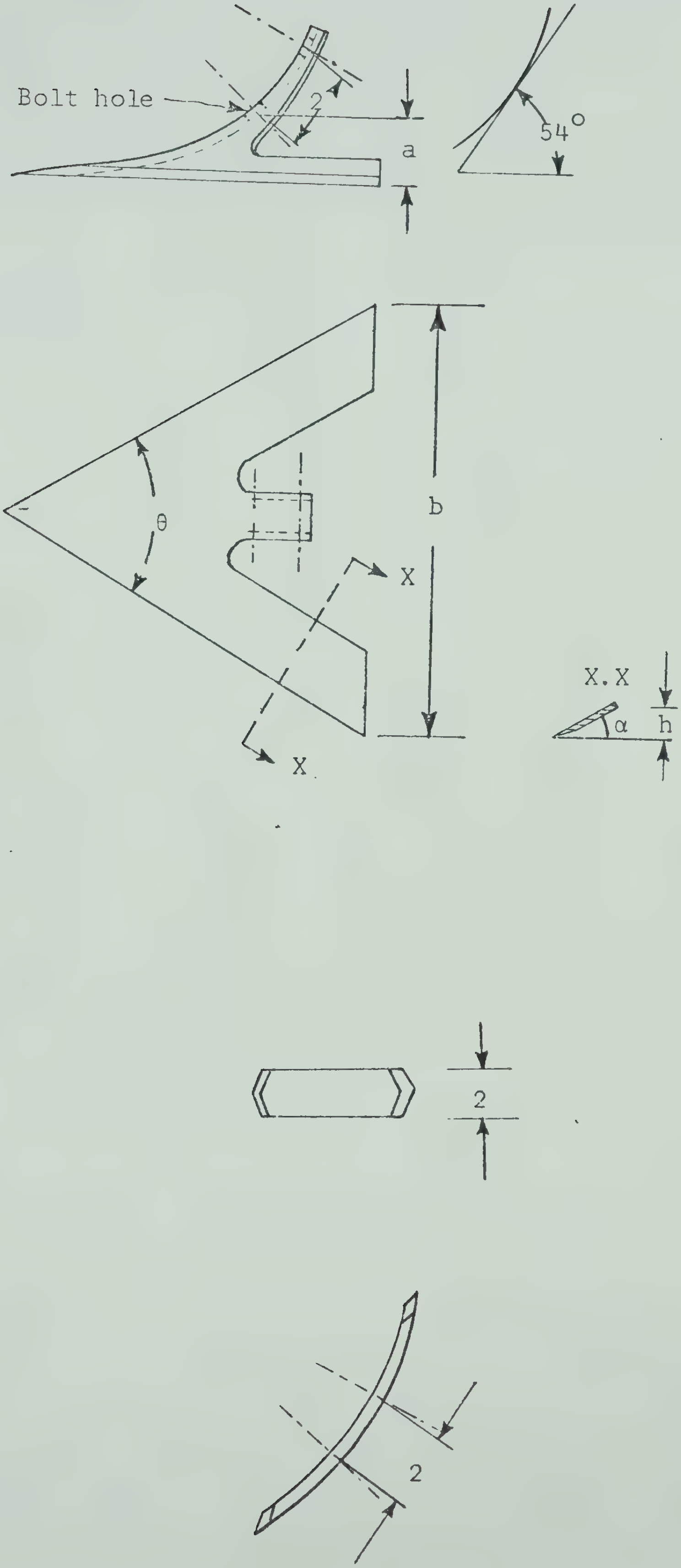
Unit of measurement - inch.

A-III: Dimensions of wheel reaction in transducer (including arrangement of gauges).



Unit of measurement - inch.

A-IV: Cultivator shank showing location of gauges on: (a) horizontal portion and (b) maximum curvature.



A-VI: Specifications for cultivator sweep and shovel mountings (ASAE Standards: ASAE S225). Top-Curved stem two hole sweep, Bottom-Two hole double pointed shovel (chisel point).

A-VI: Dimensions of sweeps and chisel point.

$15\frac{1}{2}$ in High Lift Sweep

$\theta = 69^{\circ}\ 58'$

$\alpha = 30^{\circ}$

$b = 15\frac{3}{4}$ in.

$a = 2\ \frac{9}{16}$ in.

$h = \frac{3}{2}$ in.

16. in. Low Lift Sweep

$\theta = 66^{\circ}\ 40'$

$\alpha \quad 17^{\circ}\ 50'$

$b = 16\frac{1}{2}$ in.

$a = 2\frac{9}{16}$ in.

$h = \frac{3}{4}$ in.

2 in. Chisel Point

Width of cut - 2 in.

Radius of curvature - 8 in.

APPENDIX B

B-I: Soil properties

Date	Moisture Percentage At 2 in.	4 in. Depths	6 in.	Bulk Density (dry basis) gm/cm3
2/7/70*	49.1	47.0	43.4	
2/7/70**	49.1	47.0	43.4	1.17
6/7/70*	46.0	40.0	38.4	
7/7/70*	38.3	38.9	40.6	
8/7/70*	36.3	37.9	40.7	1.01
9/7/70*	34.6	36.4	38.5	
14/7/70*	38.0	40.6	41.0	
15/7/70*	37.6	38.9	35.8	
16/7/70*	39.0	40.4	41.9	1.05
17/8/70*	35.4	37.8	39.3	
18/8/70*	34.7	37.1	36.4	
19/8/70*	37.3	38.0	35.3	
20/8/70**	32.8	32.0	30.4	1.16
21/8/70*	35.1	37.6	39.6	
25/8/70*	34.1	34.1	34.0	1.02
26/8/70*	29.5	30.1	29.5	
27/8/70**	30.4	33.0	34.1	1.17
9/9/70*	33.4	32.1	32.6	1.09
10/9/70**	32.5	32.6	33.4	1.16

Note: * Normal soil plot.

** Compacted soil plot.

The field tests were carried out at the Ellerslie Research Farm of the Department of Agricultural Engineering, University of Alberta. The soil of this area is Ellerslie loam. The test plots were fairly representative of the area. The land (summer fallow) was cultivated, disced, and harrowed 15 days before the start of field tests.

B-I: Contined

Penetrometer resistance.

Date	Depth in.	Percentage Moisture Content	Penetration resistance (psi) Normal Soil Rep. 1	Normal Soil Rep. 2	Compacted Soil Rep. 1	Compacted Soil Rep. 2
22/9/70	2	30.2	32.5	65.0	*	*
	4	32.7	95.0	80.0	*	*
	6	34.9	150.0	220.0	305.0	340.0
	8	34.7	262.5	275.0	275.2	322.5
	10	32.7	275.0	215.0	185.0	300.0
	12	31.5	245.0	200.0	167.8	252.0
30/9/70	2	36.5	32.5	32.5	667.5	597.5
	4	38.4	46.5	40.0	332.5	602.5
	6	33.8	47.5	42.5	356.5	340.0
	8	32.6	292.5	292.5	425.0	330.2
	10	37.9	275.0	262.5	380.0	267.5
	12	35.8	262.5	267.5	387.5	300.0

Note: * - Data not available.

B-II. Forces measured on the cultivator with various combinations of rows using 15½ in. high lift sweep. F - Front Row (4 shanks), M - Middle Row (4 shanks), L - Last Row (5 shanks)

Date	Depth (in.)	Speed (mph)	Forces on Hitch Horizontal Force (lb.)	Forces on Hitch Vertical Force (lb.)	Wheel Reaction (lb.)	Rolling Resistance (lb.)	Forces on Shank Horizontal Force (lb.)	Forces on Shank Vertical Force (lb.)	No. of Rows
5/8/70	**	1.57	3000.0	155.4	2468.0	330.7	217.6	14.6	3
5/8/70	**	1.54	2998.0	173.2	2672.0	358.0	202.0	29.3	3
5/8/70	**	1.48	2793.0	218.4	2496.0	334.5	189.8	15.4	3
6/8/70	**	1.59	2175.0	167.8	1882.75	252.0	210.2	14.6	2(F+M)
6/8/70	**	1.60	1869.8	176.2	1833.0	245.0	162.6	4.4	2(F+M)
6/8/70	**	1.63	2293.2	66.6	2082.5	279.0	184.7	7.3	2(M+L)
6/8/70	**	1.56	3116.4	73.7	2426.5	310.0	351.7	51.2	2(M+L)
6/8/70	**	1.66	1090.0	94.1	1717.0	230.0	239.3	10.24	1(M)
6/8/70	**	1.66	970.0	78.1	1736.0	232.6	202.4	7.3	1(M)
7/8/70	**	1.70	2299.1	121.2	1838.0	246.3	161.9	-16.1	2(F+L)*
7/8/70	**	1.62	2634.2	131.2	1746.0	234.0	167.5	9.5	2(F+L)
7/8/70	**	1.68	1020.0	124.8	1598.0	200.8	166.0	-19.0	1(F)
7/8/70	**	1.67	970.2	126.5	1578.5	211.5	165.5	-21.2	1(F)
7/8/70	**	1.58	1675.8	59.0	1910.0	255.9	270.7	14.6	1(L)
7/8/70	**	1.49	1881.0	42.2	1940.0	260.0	286.1	18.3	1(L)

Note: ** - Ram setting for 4 in. depth.

* - Shank force transducer in first row.

B-III. Forces measured on the cultivator (first and second rows) using 15½ in. high lift sweep.

Date	Depth (in.)	Speed (mph)	Forces on Hitch Horizontal Force (lb.)	Forces on Hitch Vertical Force (lb.)	Wheel Reaction (lb.)	Rolling Resistance (lb.)	Forces on Shank Horizontal Force (lb.)	Forces on Shank Vertical Force (lb.)
17/8/70*	4.1	1.58	2163.8	187.8	1826.0	244.7	233.4	-2.2
17/8/70*	4.1	2.96	2352.0	175.4	1786.0	239.3	237.56	1.5
17/8/70*	4.1	4.53	2446.1	186.0	1786.0	239.3	281.3	-8.8
18/8/70*	4.5	1.31	2116.8	176.71	1726.0	231.3	243.6	5.1
18/8/70*	4.2	2.52	2175.6	115.0	1758.0	235.6	213.8	3.7
18/8/70*	3.9	4.53	2557.8	218.9	1758.0	235.6	325.6	24.2
19/8/70*	6.2	1.30	3122.3	272.0	2013.75	269.0	383.3	25.6
19/8/70*	6.1	2.83	4351.2	300.1	1834.0	245.8	519.2	93.7
19/8/70*	6.2	3.98	3904.3	228.2	2466.0	330.4	519.7	114.2
19/8/70*	6.1	1.24	3063.4	170.1	1946.0	260.8	408.8	59.3
19/8/70*	6.2	2.58	3422.2	139.4	1926.0	258.1	420.2	-26.3
19/8/70*	2.4	1.70	793.8	93.7	1686.0	225.9	67.3	-6.5
19/8/70*	3.0	3.49	999.6	111.0	1706.0	228.6	75.6	-6.6
19/8/70*	3.2	4.59	1176.0	120.3	1786.0	239.3	104.5	-9.5

Cont'd.

B -III. Continued

Date	Depth (in.)	Speed (mph)	Forces on Hitch Horizontal Force (lb.)	Forces on Hitch Vertical Force (lb.)	Wheel Reaction (lb.)	Rolling Resistance (lb.)	Forces on Shank Horizontal Force (lb.)	Forces on Shank Vertical Force (lb.)
19/8/70*	3.0	1.33	838.0	111.0	1926.0	258.1	55.7	-14.6
19/8/70*	2.7	3.24	1046.6	103.5	1786.0	239.3	67.3	-19.0
19/8/70*	2.8	4.59	1170.1	139.0	1986.0	266.1	131.6	-41.0
25/8/70*	2.6	1.71	676.0	88.8	1906.0	255.4	50.6	-7.3
25/8/70*	2.5	2.62	764.0	77.7	1866.0	250.0	57.2	-11.7
25/8/70*	2.7	4.55	970.0	104.8	1926.0	252.5	84.2	-2.2
25/8/70*	4.1	1.75	1881.6	178.5	1926.0	258.1	193.0	8.8
25/8/70*	4.2	2.73	1940.4	208.7	1946.0	260.8	195.6	12.4
25/8/70*	4.3	4.26	2646.0	200.7	2090.0	280.0	315.7	30.7
25/8/70*	5.8	1.52	2375.5	241.9	2266.0	303.6	272.5	53.4
25/8/70*	6.0	2.62	3880.0	301.9	2246.0	295.0	450.0	65.9
25/8/70*	6.1	3.59	4704.0	324.1	2246.0	303.6	527.8	72.4
			16 in. Low Lift Sweep					
26/8/70*	4.0	1.63	1705.0	178.9	1358.0	182.0	166.7	-28.5
26/8/70*	4.0	3.39	2058.0	212.7	1626.0	217.9	201.8	-24.4
26/8/70*	3.9	4.55	2416.0	224.2	1726.0	231.2	259.3	-30.0

Cont'd.

B-III. Continued

Date	Depth (in.)	Speed (mph)	Forces on Hitch Horizontal Force (lb.)	Forces on Hitch Vertical Force (lb.)	Wheel Reaction (lb.)	Rolling Resistance (lb.)	Forces on Shank Horizontal Force (lb.)	Forces on Shank Vertical Force (lb.)
26/8/70*	5.8	1.77	2998.0	266.4	2122.0	284.3	359.5	57.8
26/8/70*	5.9	3.59	3516.0	276.6	1926.0	258.1	437.7	36.6
26/8/70*	5.6	4.08	2998.0	275.5	1906.0	255.4	378.2	15.4
26/8/70*	4.0	3.25	2528.4	241.1	1826.0	244.7	258.3	0.0
26/8/70*	4.0	4.01	2998.0	226.0	1790.0	284.3	355.2	0.7
27/8/70*	4.4	1.71	1969.8	217.1	1906.0	255.4	255.3	15.4
27/8/70*	5.3	3.41	2528.4	223.8	2066.0	276.8	285.6	8.0
27/8/70*	4.8	4.01	2443.5	217.1	1906.0	255.4	255.0	1.5
27/8/70*	6.6	1.70	3116.0	234.4	2426.0	325.1	320.3	26.4
27/8/70*	6.2	3.59	2910.6	233.1	2146.0	287.6	281.8	-44.6
27/8/70*	6.2	4.01	3733.0	277.5	2306.0	309.0	404.0	63.7
				2 in. Chisel Point				
9/9/70*	4.6	1.54	1413.1	114.1	2086.0	279.5	135.9	13.2
9/9/70*	4.5	3.40	1617.0	143.9	2106.0	298.3	155.6	25.6
9/9/70*	4.4	4.86	1999.2	163.4	2066.0	287.6	211.5	22.7
9/9/70*	4.8	1.62	1528.0	135.0	2226.0	303.6	137.9	40.3
9/9/70*	4.4	3.24	1611.1	143.4	2226.0	309.0	177.8	23.4
9/9/70*	4.4	4.86	1881.6	164.4	2266.0	303.0	194.3	23.5

Cont'd.

B-III. Continued

Date	Depth (in.)	Speed (mph)	Forces on Hitch Horizontal Force (lb.)	Forces on Hitch Vertical Force (lb.)	Wheel Reaction (lb.)	Rolling Resistance (lb.)	Forces on Shank Horizontal Force (lb.)	Forces on Shank Vertical Force (lb.)
				15½ in. High Lift Sweep				
10/9/70*	4.3	1.54	2234.4	220.7	1946.0	260.7	253.7	12.4
10/9/70*	4.2	3.09	1999.2	188.7	1906.0	250.0	212.5	7.3
10/9/70*	4.3	4.53	2646.0	225.0	2026.0	276.7	337.7	-25.6
20/8/70**	4.3	1.66	3134.0	212.2	2226.0	120.2	361.5	49.0
20/8/70**	4.2	3.09	3704.0	231.3	2306.0	124.5	455.9	73.2
20/8/70**	4.5	1.66	3140.0	259.7	2006.0	108.3	382.8	122.2
20/8/70**	4.1	3.24	3381.0	248.6	2066.0	111.6	410.4	82.7
				2 in. - Chisel Point				
10/9/70**	4.4	1.54	2205.0	202.5	2346.0	126.7	279.0	62.2
10/9/70**	4.1	3.09	2763.0	324.1	2386.0	133.1	280.9	80.5

Note: * - Normal Soil

** - Compacted Soil.

B-IV: Calculated percentage of random error in the forces based on samples.

Number of runs used in calculation	P_H	P_V	W_R	R.R.	L	V
			Three rows			
3	3.5	17.2	4.0	4.0	60.0	37.12
			First rows			
2	2.5	0.7	2.6	2.6	0.5	5.0
			Third row			
2	2.9	16.6	0.8	0.8	2.8	11.2
			Second row			
2	4.3	9.3	1.8	1.8	8.5	0.0
			First and second rows			
4	3.0	0.3	4.6	4.6	2.6	1.1

B-V: Correction of P_V considering possible non-horizontality of the hitch link transducer.

Date	P_V (measured) lb.	P_V (by moment) lb.	P_V (corrected for non-horizontality) lb.	Depth in.	Speed mph
25/8/70	104.8	220.0	231.0	2.7	4.55
18/8/70	218.9	399.8	623.0	3.9	4.53
19/8/70	300.0	730.0	885.0	6.1	2.83
25/8/70	77.7	193.0	175.5	2.5	2.62
18/8/70	110.0	197.0	237.8	3.0	1.33
19/8/70	103.5	225.0	229.0	2.7	3.24
25/8/70	242.0	432.0	527.0	5.8	1.52
25/8/70	302.0	684.3	690.0	6.0	2.62
25/8/70	200.7	462.1	439.2	4.3	4.26
25/8/70	208.7	353.8	445.4	4.2	2.73
7/8/70	124.0	251.9	266.8	*	1.68
7/8/70	59.0	191.6	154.5	*	1.58
6/8/70	94.1	210.3	203.1	*	1.66

* - 4 in. depth (by hydraulic ram setting)

B-VI: Static weight of cultivator.
(Cultivator levelled at 15 in. drawbar height and 4 in. depth)

Row of Cultivator	Weight on Wheels lb.	Weight on Hitch lb.	Total Weight lb.
First row	1713.0	105.5	1818.5
Second row	1771.5	47.0	1818.5
Third row	1910.0	-37.5	1872.5
First and Second Rows	1969.5	71.0	2040.5
First and Third Rows	2116.5	-14.5	2102.0
Second and Third Rows	2180.5	-78.0	2102.0
Three rows	2363.0	-38.5	2324.5